WATER FLOW THROUGH GEOTEXTILES USED TO SUPPORT THE ROOT ZONE OF TURFGRASS ON SPORTS FIELDS

A Thesis

by

KEISHA MARIE ROSE-HARVEY

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2009

Major Subject: Water Management and Hydrological Science

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Approved by:

Chair of Committee,	Kevin McInnes
Committee Members,	Anthony Cahill
	Richard White
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ABSTRACT

Water Flow Through Geotextiles Used to Support the Root Zone of Turfgrass on Sports Fields. (August 2009)

Keisha Marie Rose-Harvey, B.Sc., University of the West Indies

Chair of Advisory Committee: Dr. Kevin McInnes

A sports field construction method that uses a geotextile to support the root zone atop a synthetic drainage structure is an alternative to the common design that uses gravel drainage material to support the root zone. A study was conducted to address the concern that fine particles in the root zone may migrate under the influence of percolating water, clog geotextile pores, and restrict the amount of water drained from a sports field. In test columns, six root zone mixtures with different particle size distributions were combined with ten geotextiles with different opening sizes to produce 60 replicated treatments. Water flow through the root zone mixture-geotextile combinations in the test columns was evaluated over a six-month period. Change in permeability was assessed by monitoring the temporal distribution of drainage from a 25-mm pulse of water applied to 300-mm deep root zone mixture in the test column. Particles in drainage water were analyzed for size distribution. The study revealed that drainage rates were affected more by drainage trough the root zone mixture than through the geotextile. The amount and particle size distribution of particles in drainage water were influenced more by root zone mixture than by geotextile. It appeared that in the

establishment phase of a sports field that fine particles in the root zone may present more of a problem to clogging of the root zone pores than clogging of the geotextile pores.

DEDICATION

This thesis is dedicated to the all knowing, ever present God. He is the one with whom all knowledge and wisdom begins.

ACKNOWLEDGEMENTS

I would like to express gratitude to my committee chair, Dr Kevin McInnes, for his patience and guidance throughout this research program. I am also thankful to my committee members, Dr. Richard White and Dr. Anthony Cahill, for their contributions to the successful completion of my studies.

Thanks to everyone at Texas A&M University that helped to make my experience a great journey and stepping stone to my future. Finally, but by no means least I must say thanks to my husband who offered so much encouragement along the way.

NOMENCLATURE

AOS	Apparent Opening Size
ASTM	American Society of Testing and Materials
PA	Polyamine
PE	Polyethylene
PET	Polyester
PP	Polypropylene
PVC	Polyvinylchloride
USGA	United States Golf Association

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CHAPTER I

INTRODUCTION

Sporting activities such as baseball, football, golf and soccer that are played on turfgrass have become an integral part of American life. The large social and economic investments into these activities necessitate durable, safe, and healthy field surfaces (Brown and Duble, 1975; Puhalla et al., 1999).

High-quality, turfgrass-based fields should be resistant to compaction and drain quickly after rainfall and irrigation events (Brown and Duble, 1975; Puhalla et al., 1999; Taylor et al., 1997). Rapid drainage promotes healthy turfgrass growth, as plant roots rely on adequate aeration and do not tolerate saturated conditions for extended periods of time. Rapid drainage also ensures that play can be resumed soon after heavy rain or irrigation. While rapid drainage is a necessity, it is also important that fields are capable of storing adequate water for plant growth.

Sports field designers have experimented with various mixtures of soils, sands, and organic materials to meet the requirements for drainage, compaction resistance, aeration, and water-holding capacity. Because sand-based mixtures possess many of these characteristics, they have become the most popular choice for sports fields (Puhalla et al., 1999).

This thesis follows the style of Crop Science.

Field Designs

The United States Golf Association (USGA) design for putting greens is a popular sand-based design for other sports fields. Fields that are constructed according to the USGA recommendations (USGA, 1993) have a sand-based root zone mixture placed atop gravel drainage material, typically 30 cm over 10 cm, respectively (Figure 1).

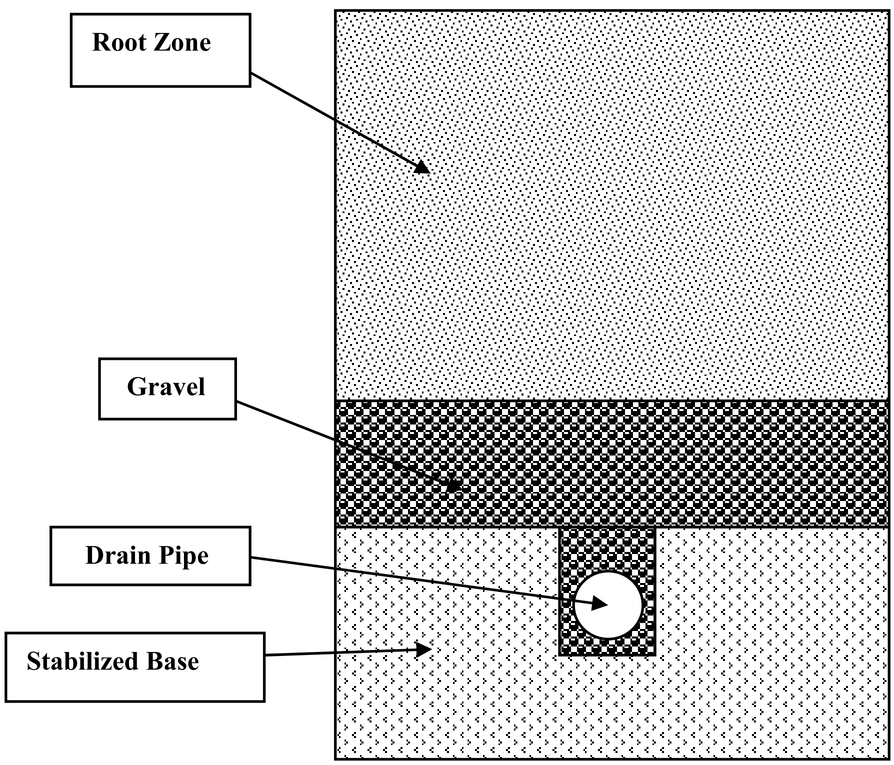

Fig.1. Schematic of USGA putting green design.

The gravel drainage layer is essential for the rapid lateral movement of water to drainage pipes. When the root zone water is under tension the gravel layer slows gravitational water loss due to an appreciably lower unsaturated hydraulic conductivity in the gravel, than the sand, with increasing tension. The amount of water held in the root zone is a function of the depth and particle size distribution of the gravel in the drainage layer, as well as the particle size distribution of the root zone (Taylor et al., 1993; Taylor et al., 1997). Water holding capacity of a given root zone is generally greater in the presence of a coarse gravel layer than a fine gravel layer because the unsaturated hydraulic conductivity of the coarse gravel drops faster with tension than it does with fine gravel.

The gravel drainage layer may be replaced with other suitable materials or structures. One such alternative (Airfield design, Airfield Systems, Edmund, OK) utilizes a 25-mm thick plastic grid with large void spaces, and a geotextile to support the root zone mixture atop the grid (Figure 2). The geotextile is chosen according to considerations of both retention of the root zone mixture and permeability to water (Giroud, 2005). The geotextile must retain the bulk of the root zone particles so as to prevent the large drainage pores in the plastic grid from filling, while allowing migrating fine particles to flow through so as not to clog the geotextile and restrict drainage from the root zone (Luettich et al., 1992; Mlynarek et al., 1991; Sarsby, 2007). There are a wide variety of commercially available geotextiles suitable to use in the Airfield design, although none have been specifically manufactured for such use and few have been tested in the design.

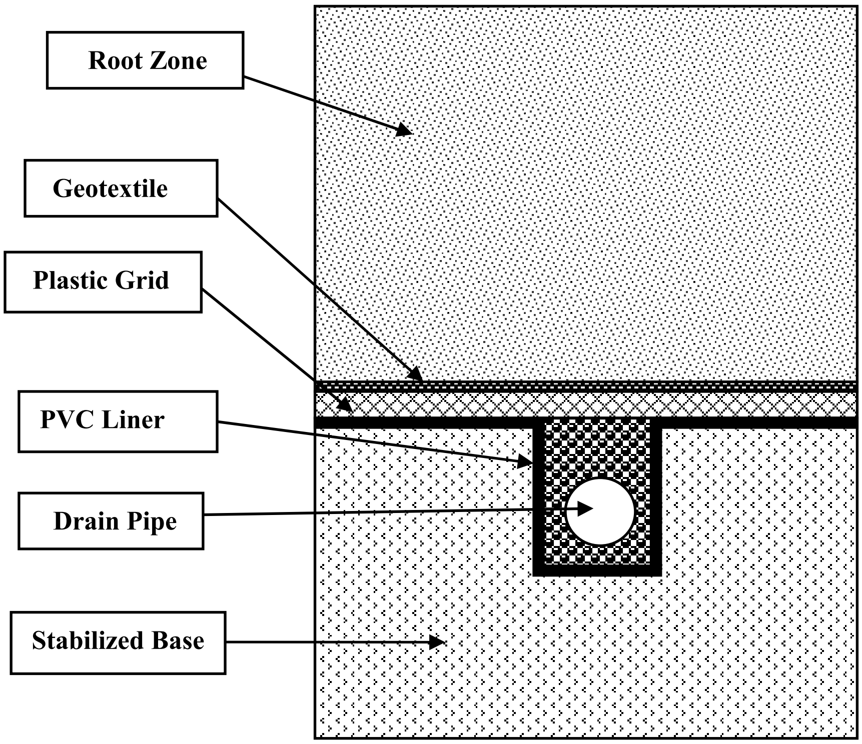

Fig.2. Schematic of Airfield Systems sports field design.

Geotextiles

Geotextiles are most often manufactured from synthetic materials. These materials include filaments of the polymers polypropylene (PP), polyethylene (PE), polyester (PET), polyamide (PA), and polyvinylchloride (PVC) (John, 1987; Koerner, 1998; Sarsby, 2007). These filaments are then woven, tangled, or bonded to form a textile.

Woven geotextiles are produced mechanically by weaving monofilaments or multifilaments (Figure 3). Nonwoven geotextiles have filaments that are chemically, mechanically, or thermally bound. Filaments in chemically bonded nonwoven

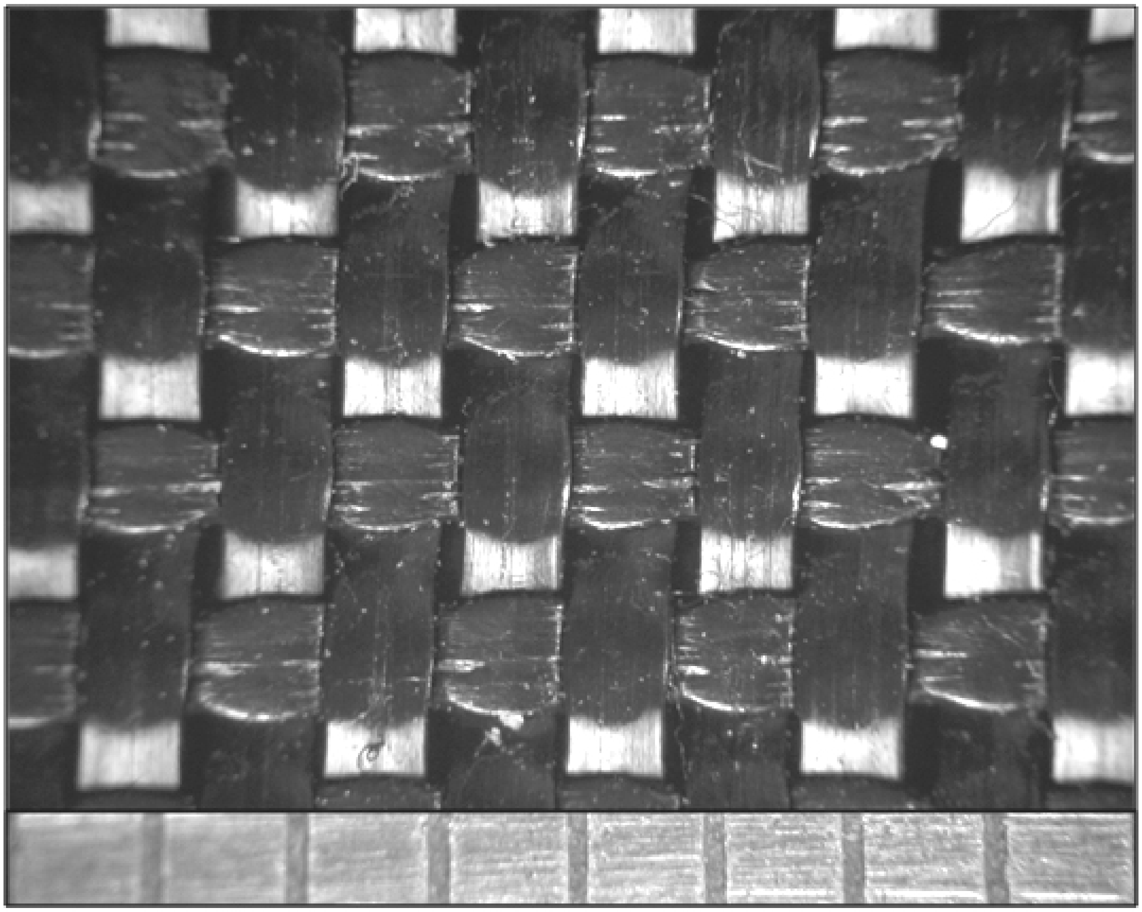

Fig.3. Woven geotextile (scale shown at the bottom is 1.6 mm between tick marks).

geotextiles are usually bound during the filament extrusion process by applying binding agents such as acrylic resin (John, 1987; Koerner et al., 1993). Mechanically produced nonwoven geotextiles have filaments that are entangled with barbed needles (needle punched) or water jets (hydro-entangled). To make the needle punched fabrics, reciprocating needle barbs are used to interlock and entangle a fibrous web of filaments. Some needle punched geotextiles are further processed so that filaments on one or both sides of the textile are thermally or chemically bonded. The end product of the needle punch process is a felt-like textile (John, 1987; Koerner, 1998) (Figure 4). Nonwoven

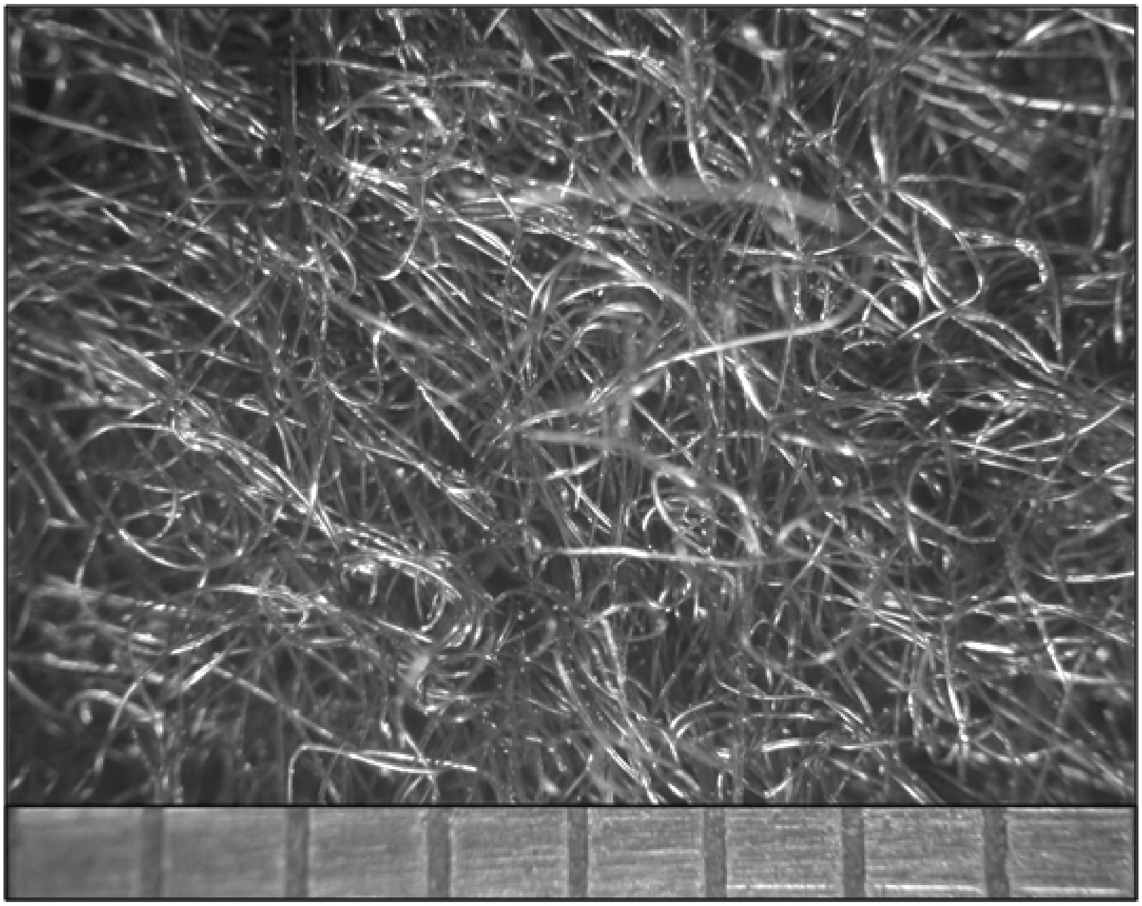

Fig.4. Nonwoven needle punched geotextile (scale shown at the bottom is 1.6 mm between tick marks).

geotextiles that are thermally bonded are produced using a heated roller to partially melt some filaments and bind to others where they touch (John, 1987). Nonwoven geotextiles that are produced from monofilaments that are spun on to a table and then thermally or chemically bonded are commonly referred to as spunbond geotextiles (Figure 5). Some of the physical properties that are affected by the choice of manufacturing process include strength, mass per unit area and thickness. Needle punched geotextiles are

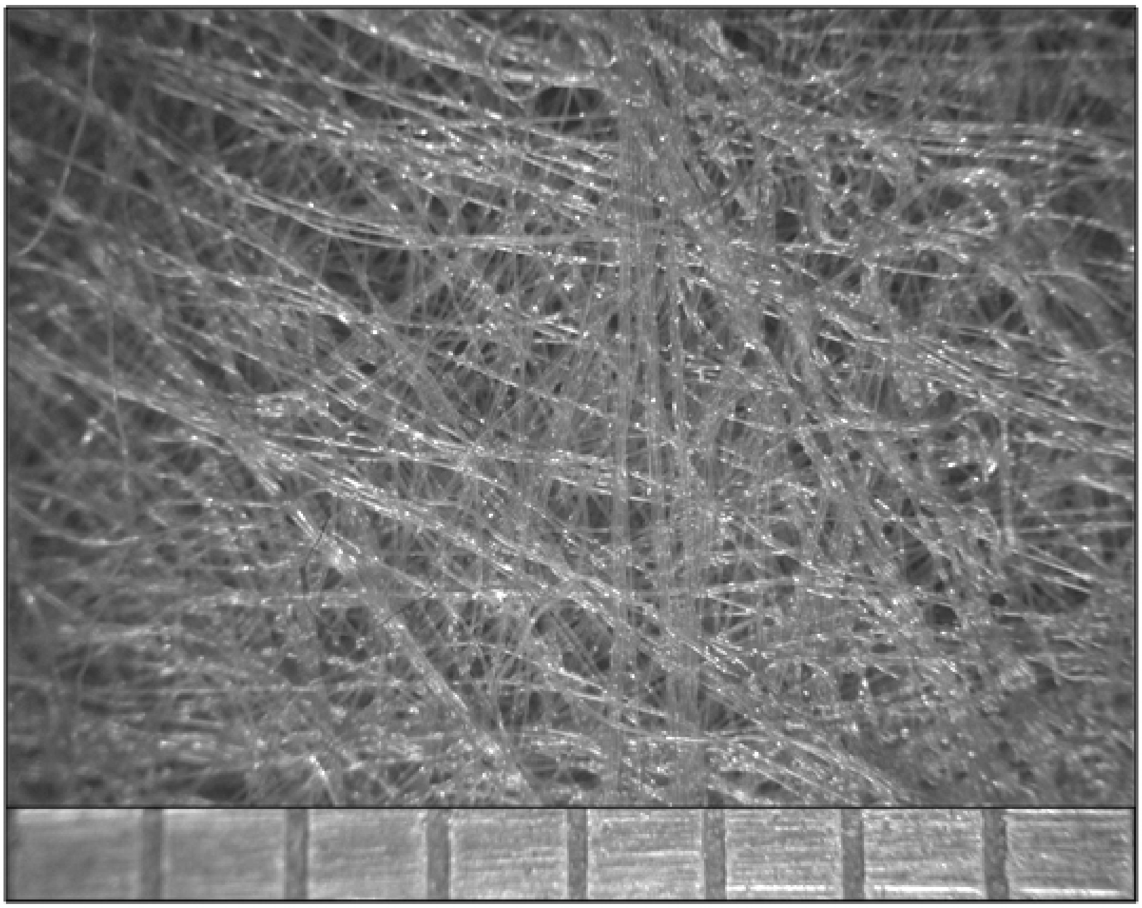

Fig.5. Spunbond geotextile (scale shown at the bottom is 1.6 mm between tick marks).

usually thicker and have higher mass per unit area than spunbond geotextiles. Spunbond geotextiles generally have higher strength than needle punched geotextiles (Koerner, 1998). The manufacturing process used also affects the size distribution of pores (voids) in a geotextile. In general, the pores within a woven geotextile are more regularly spaced than in a nonwoven type. In needle punched fabrics, the thickness of the material influences its pore size distribution, but this not usually the case for spunbond materials (Bhatia and Smith, 1995).

When choosing a geotextile for hydraulic applications such as in sports fields, it is important to have information about its pore size distribution, as well as the particle size distribution of the root zone mixture that it will support. Pore size distributions of geotextiles have been evaluated by several methods. These methods include mercury intrusion (Prapaharan et al., 1989), bubble pressure (Bhatia and Smith, 1995), hydrodynamic sieving (Fayoux, 1977), and dry sieving (Gerry and Raymond, 1983). The pore size distribution obtained is somewhat dependent on the method used and there is considerable disagreement on which method produces the most accurate measure (Bhatia and Smith, 1995). It is, however, common for pore size distribution to be described by a particle retention criterion such as apparent opening size (AOS) that is determined through dry sieving. The AOS refers to the diameter or width of a pore (opening) where 95 % of the pores in the geotextile are smaller, often symbolized as O_{95}. To determine AOS, a geotextile specimen is placed in a frame, sized glass beads are placed on the geotextile surface, and the geotextile and frame are shaken such that the motion gives the beads the opportunity to pass through the test specimen. The procedure is repeated on the same geotextile specimen with various size glass beads until the diameter where 5% or less of the beads pass through the geotextile and may be determined from a plot of percent passing vs. bead diameter (ASTM, 2004a). The information obtained from this method essentially gives an estimate of the size of the largest particle that can pass through the geotextile (Sarsby, 2007). In some cases, the characteristic opening size is specified by an O_{50} or O_{90} value, referred to as an equivalent opening size (EOS) (Sarsby, 2007). There are other important physical properties that are determined for geotextiles, which may be important considerations for hydraulic applications. This includes the determination of the water flow rates within individual geotextiles (ASTM, 2004b).

Geotextile Clogging

The installation of a sport field that incorporates a geotextile and an engineered synthetic drainage structure has its advantages and appeal. Because of the cost and time required to construct a sports field, there has been concern about both the short and long-term performance of such fields. Once a field has been put in place, the hope is that it functions as intended, requires low maintenance (Brown and Duble, 1975), and has a relatively long lifetime of usage. Of particular concern is whether the pores in the installed geotextile will become clogged and restrict drainage of water from irrigation and precipitation. Reduced drainage rate can lead to the partial or total failure of a field through effects such as longer delays before play resumption, increased turfgrass disease, and higher maintenance cost.

Clogging of geotextiles may be caused by combinations of chemical, biological and physical processes. Flow of water within geotextiles can be altered if minerals or chemicals precipitate or bacteria grow on or within the body of geotextiles (Koerner et al., 1988; Rollin and Lombard, 1988). Such phenomena have been extensively studied (de Mendonca and Ehrlich, 2006; de Mendonca et al., 2003; Palmeira et al., 2008). The focus of the research described in this thesis was on physical clogging caused by particles migrating to the geotextile from the root zone mixture.

Rollin and Lombard (1988) suggest that there are three physical mechanisms through which particles can restrict water flowing through a geotextile: blocking, blinding, and clogging. Blocking occurs when particles that have migrated to the media-geotextile interface lodge themselves over pores in the geotextile. Blinding occurs when particles that are larger than the geotextile pores trap finer particles, forming a layer that has reduced permeability atop the geotextile (also called a cake layer) (Rollin and Lombard, 1988). Rollin and Lombard (1988) subsequently differentiated these two mechanisms from clogging where particles lodge within the pores of the geotextile body. Some authors refer to all three mechanisms as clogging (e.g., Giroud, 2005), as will be done in this thesis.

Tests to Assess Clogging

Clogging that occurs in an installed geotextile can cause it to lose an appreciable fraction of its permeability, potentially leading to an expensive problem to correct. This risk necessitates the evaluation of geotextiles to determine suitability for specific applications under expected hydraulic conditions (Rollin and Lombard, 1988). Over the past few decades several studies have been geared towards the design of tests that could facilitate the evaluation of a geotextile's potential to clog. These have taken the form of laboratory and field investigations.

The Gradient Ratio (GR) test was developed by the United States Army Corp of Engineers (USACE) to determine the compatibility of particular soil-geotextile combinations (Koerner, 1998). In the GR test, soil is packed on top of a geotextile sample that has been placed inside a vertical column. Water is allowed to flow through the geotextile and soil samples for 24-h during which hydraulic head is measured at several locations in the column (Rollin and Lombard, 1988). Hydraulic gradients are calculated from the hydraulic heads. The GR value for the system is determined as the ratio of the hydraulic gradient of the combined lower 25 mm of soil and geotextile and the hydraulic gradient of the adjacent 50 mm of soil. The USACE has recommended that GR be no more than 3. Values equal to or less than this are used to indicate a compatible combination, one not likely to clog (Koerner, 1998). One of the main advantages to the test is the relatively short time over which results can be obtained. There are however several identifiable disadvantages such as, preferential flow along the test column's walls (Rollin and Lombard, 1988), piping of soil along the walls of the test column, the occurrence of air pockets both in the soil and geotextile, and concerns about the reliability of the GR value for long-term applications (Koerner, 1998).

Long-term filtration tests have been also used to evaluate the compatibility of soil-geotextile combinations. The procedures used for these tests are similar to that used for the GR test. The time over which the soil-geotextile system is evaluated is much longer than 24-h, in some cases 1000-h (Koerner, 1998). Inflow of water is usually kept at constant head and the permeability of the soil-geotextile system and the mass of the particles that pass through the geotextile are noted. The test usually commences with a loss of fine particles through the geotextile's pores, which allows initial outflow rates to be high (Rollin and Lombard, 1988). Over time, the test soil forms of a "soil cake" at the soil-geotextile interface. This cake prevents the further loss of soil particles and stabilizes outflow. Maximum clogging is thought to have occurred when the flow becomes constant.

Other laboratory tests that can be used to assess the clogging potential of geotextiles include the fine fraction filtration F^3 test (Sansone and Koerner, 1992). As indicated by its name, the entire particle size distribution of a soil is not used in this test, but rather specific particle size ranges. These particles are usually made into slurry and added to a test column that contains a geotextile specimen. The F^3 test is deficient in indicating geotextile behavior with an *in situ* soil. It is likely that an *in situ* soil would prevent the immediate contact between most fine particles found within its body and the geotextile. Sansone and Koerner (1992) identified this inherent problem and implied that this test might not be suitable for situations where the geotextile is in intimate contact with the soil placed above it.

While several short and long-term laboratory tests exist to evaluate clogging in geotextiles, a very limited number of studies have attempted these evaluations in designs and with materials used in sports fields. In a 12 year study, Callahan et al (2001) assessed the performance of several geotextiles (woven and nonwoven) used as separators between a single root zone mixture and a gravel sub-layer. The root zone mixture used was chosen to meet USGA recommendations of 1973. Although considerable particle migration through the root zone occurred, no significant levels of geotextile clogging were observed (Callahan et al., 2001). It appears that more research is warranted to evaluate geotextiles of various AOS and construction in combination with root zone mixtures of different particle size distribution. This research would give insight into the suitability of using geotextiles of a given AOS with root zone mixtures of given particle-size distributions.

Research Objectives

The purpose of the study was to combine geotextiles of different construction type and different pore-size distribution with root zone mixtures of varying particle-size distributions, to assess the potential for clogging from fine particles ($d<150$ μm - very fine sand, silt, and clay) that have been observed to migrate from root zone mixtures under irrigation and rainfall events. The research was focused on the temporal changes in drainage in the first six months of the establishment of a sports field. The specific objectives were to:

- Evaluate the temporal changes in whole-system drainage rates from test columns that contain a particular combination of one of 6 different root zone mixtures and one of 10 geotextiles placed over a 25-mm deep plastic drainage grid.

- Assess whether any temporal changes in the fraction of water drained from these test columns were due to clogging of geotextiles.

CHAPTER II

MATERIALS AND METHODS

Experimental Design

The study was conducted at Texas A&M University, College Station. Six root zone mixtures, supported by a 25-mm deep porous grid, were combined with each of 10 different geotextiles (60 treatments) and replicated three times in test columns (180 columns). The root zone mixtures had systematic differences in particle size distribution. The test columns were used to assess whether fines migrating with water draining from the root zone mixtures during the establishment of a sports field would clog the geotextiles. The study was carried out over a six month period from June to December, 2008.

Characterization of Materials

Two woven, three spunbond, and five needle punched geotextiles were used in the study. The manufacturer's specifications for these geotextiles are shown in Table 1.

The six root zone mixtures were made from different ratios of three parent materials, a sand meeting USGA recommendations PM1 (US Silica Company, Kosse, Texas), a sand with fines (particles <150 μm) in excess of USGA recommendations PM2 (Living Earth, Houston, TX), and a sandy clay loam PM3 from a pasture near College Station, TX. The particle size distributions of the sand portions of PM1 and PM2 were determined by sieve analysis (Gee, 2002). The sieves used were: 2.0 mm (No.10), 1.0

mm (No. 18), 500 µm (No.35), 250 µm (No. 60), 150 µm (No. 100), and 106 µm (No. 140). The silt and clay fractions were washed through a 53 µm (No. 270) sieve and the particle size distributions were analyzed with a laser particle size analyzer (Model LS230, Beckman Coulter Inc., Fullerton, CA) calibrated with Coulter Latron™ 300 LS control. The particle size distribution of PM3 was determined using the hydrometer method (Gee, 2002).

Table 1. Properties of the geotextiles used in the study.

Distributor	Geotextile	Type†	Material ‡	AOS (mm) §	Thickness (mm) ¶	Weight (g/m^2)	Water Flow Rate (mm/s) #
GSE Lining	GSENW16	N	PP	0.150	3.94	540	34
GSE Lining	GSENW10	N	PP	0.150	2.54	335	58
Propex	NW401	N	PP	0.212	NA	182	95
Propex	NW1001	N	PP	0.150	NA	346	58
Propex	NW351	N	PP	0.300	NA	169	102
Propex	WM104F	W	PP	0.212	NA	215	12
TenCate	FW404	W	PP	0.425	0.89	298	48
Fiberweb	3301L	S	PP	0.3	NA	102	65
Fiberweb	3341G	S	PP	0.24	NA	115	58
Freudenberg	Lutradur	S	P	0.198	0.59	130	157

† N- Nonwoven needle punched; W-Woven; S- Spunbond
‡ PP-Polypropylene; P-Polyester
§AOS determined by ASTM D 4491-99a (2004a)
¶ NA- Not Available
#Water Flow Rate determined by ASTM D 4751- 04 (2004b)

Root Zone Mixtures

Test Mixtures

Four mass-based root zone mixtures were made from PM1, PM2, and PM3. Root zone mixture M1 was a 1:1 mixture of PM1:PM2, root zone mixture M2 was 9:1 mass-based mixture of PM1:PM3, root zone mixture M3 was a 9:1 mixture of PM2:PM3 and root zone mixture M4 was a 9:9:2 mixture of PM1:PM2:PM3. The different mixtures were blended for 30-min in a cement mixer. Samples of the all the root zone

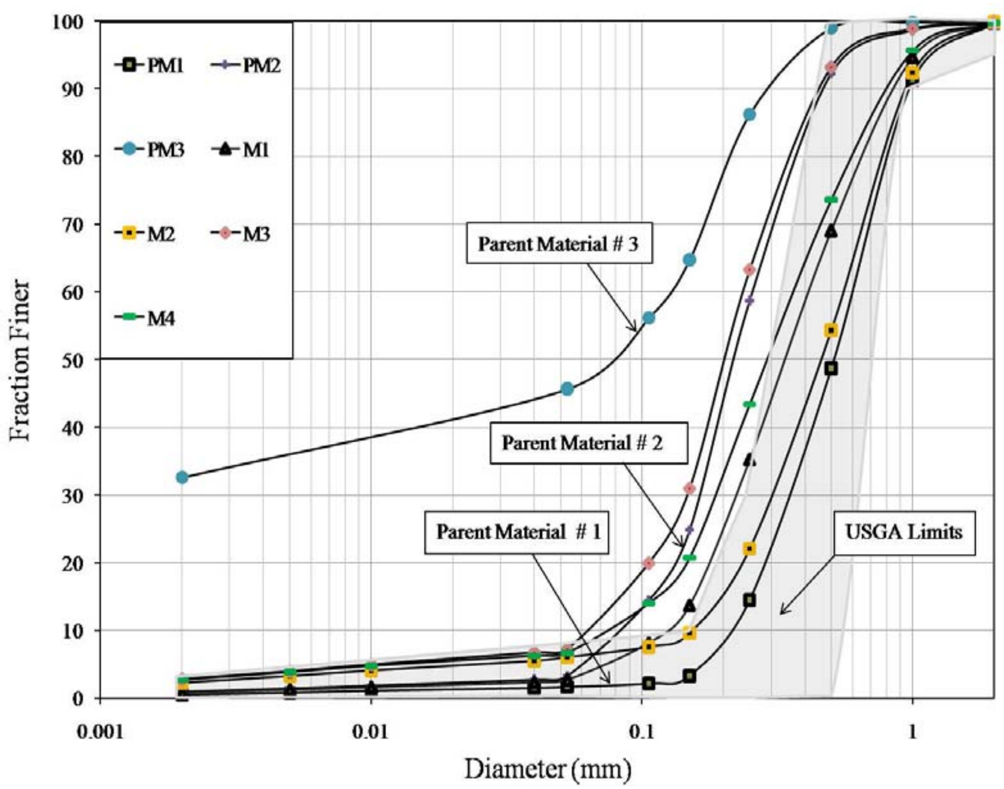

Fig.6. Particle size distributions of root zone mixtures used in the experiment.

mixtures were collected at the time of blending. The particle size distribution of the sand portions were subsequently determined in the laboratory through dry sieving and the silt and clay portions were determined with a laser particle size analyzer (Figure 6).

Determination of Bulk Densities to Pack Mixtures

One kg each of oven dried samples of PM1, PM2, and M1 were made to a gravimetric water content of w=0.05 kg/kg. Two PVC cylinders of height 11 cm and inner diameter of 7.6 cm were stacked - the bottom cylinder being pre-weighed. A 0.7 kg subsample of a root zone mixture was placed inside the cylinders. A drop-hammer device with a flat, disk-shaped foot the diameter of the inside of the cylinders was used to compact the samples according to USGA recommendations (USGA, 1993). A spatula was used to separate the bottom and top cylinders, flush with the top surface of the bottom cylinder. The mass of the wet sample in the cylinder was determined by weighing the cylinder with sample and then subtracting the mass of the cylinder. The total (wet) bulk density of the sample ρ_t was determined as:

$$\rho_t = \frac{M_t}{V_t}$$

where M_t is total mass of material and V_t is total volume of material. The dry bulk density ρ_b was determined from the wet bulk density and the gravimetric water content as:

$$\rho_b = \frac{\rho_t}{1 + w}$$

Each compaction test was done in three replicates and average bulk density calculated (Table 2). These average bulk densities were used to determine the amount of a root zone mixture that was placed in a test column. The bulk density to which root zone mixture M2 was compacted was the same as that of parent material PM1. The bulk densities of root zone mixture M3 was the same as parent material PM2, and the bulk density of root zone mixture M4 was the same as root zone mixture M1.

Table 2. Bulk densities of root zone mixtures.

Material	**Dry Bulk Density ρ_b (Mg/m^3)**
PM1	1.63
PM2	1.60
M1	1.65

Determining Mass of Root Zone Mixture to Pack in Test Columns

The depths of root zone mixtures in the 152-mm ID test columns were 300 mm. The dry mass of root zone mixture to be placed inside a test column was determined by the product of the dry bulk density and the volume (5.47×10^{-3} m^3). Enough of one of the materials to fill ten test columns was mixed in a cement mixer to produce a material with homogenous water content. The gravimetric water content of the sand was determined by drying a 50-g sample of the sand mixture in a microwave oven. This water content was then used to calculate the amount of material to place in each column using the relationship:

$$M_w = M_d \cdot (1 + w)$$

where M_w is the wet mass of material and M_d is the dry mass of material to be added to produce a desired dry bulk density.

This procedure was conducted because the containers of bulk parent material had various amounts of water in them. When a root zone mixture was to be made from the combination of several parent materials, the water contents of the individual parent materials were determined separately. They were then mixed in the appropriate ratio based on their individual water contents.

Determining the Saturated Hydraulic Conductivity

Seven hundred grams of root zone mixture was adjusted to a water content of 0.05 kg/kg and then compacted in a PVC permeameter with a 77 mm inner diameter and 110 mm height. The compaction was done with a drop-hammer device according to USGA recommendations (USGA, 1993). The permeameter was subsequently placed on top of a support screen in a funnel and water was applied to the root zone. The applied water was maintained at constant depth above the root zone surface. The water that drained through the root zone mixture was collected in a beaker and the time for a fixed volume, typically 50 mL, to be collected was noted. This measured volume per time was taken at 3 successive times after a steady flow rate was established. The saturated hydraulic conductivity was determined as:

$$Ks = \frac{V_w \cdot L}{A \cdot t \cdot (h\ + L)}$$

where K_s is the saturated hydraulic conductivity, V_w is the volume of water collected over time t, L is the depth of the root zone mixture in the permeameter and h is the depth of water above the root zone mixture.

Determining Water Holding Capacity

Root zone mixture was compacted into six PVC cylinders of 77 mm inner diameter and height 50 mm using a drop-hammer (USGA, 1993). The cylinders containing the root zone was stacked on each other. An empty cylinder was placed on top and then the 7 cylinders were then taped at the joints to make a single column. The drop-hammer compactor was then placed into the top of the column and dropped to create good contact between individual layers.

The resultant column was placed atop a piece of mesh and held vertical by a clamp and stand. The root zone was then wetted from the top with three 600 mL aliquots of water. Water was allowed to disappear from the top of the column before each successive aliquot was added. The column was then covered with plastic to prevent evaporation and allowed to stand for 24-h. This resultant soil column was then segmented into six 50 mm layers and the root zone material in the top cylinder was discarded. Each individual 50-mm layer of root zone material was weighed wet, dried at 105 °C and again weighed to determine the water content of each layer.

Column Preparation

Test columns were made from 150-mm diameter PVC sewer pipe that had been cut to 350 mm lengths and fitted with flat-bottom PVC end caps (Figure 7). A 19-mm

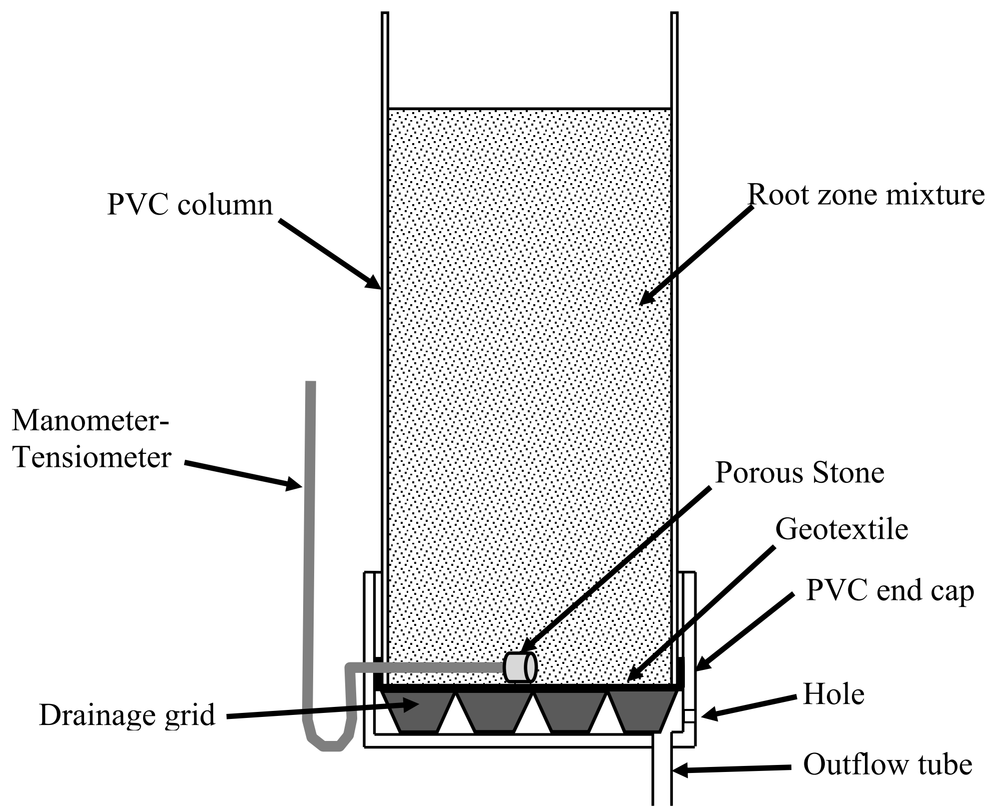

Fig.7. Cross sectional schematic of an assembled test column.

drainage hole was drilled into the base of the PVC end cap. AirDrain® grids (Airfield Systems, Edmond, OK) were cut to fit inside the PVC end cap. A circular piece of a geotextile at least 40 mm larger diameter than the PVC pipe was placed over the open end of the cap and the PVC pipe was driven downward into the cap until it touched the 25-mm deep AirDrain® grid. In doing such, the geotextile was pulled tight atop the AirDrain® grid and upward into the space between the pipe and cap, insuring that water and fines leaving the column would pass through the geotextile. With the thicker geotextiles, the inside diameter of the cap was enlarged using a lathe so that the geotextile fit in the space between the cap and pipe. The small gap between the body of the PVC pipe and the top of the end cap was sealed with caulking.

A manometer-tensiometer was constructed using a porous stone (aquarium airstone) connected to clear plastic tubing. The porous stone had an air entry water potential of about -70 mm water. A 6.4-mm hole was drilled into the side of the PVC cap and cylinder, just above the top side of the geotextile. The porous stone was placed on the top center of the geotextile and the connected plastic tubing was pushed through the hole in the side of the PVC cap. Outside the column, the tubing was bent into a U-shape so that it extended 30 mm below the height of the geotextile (the level of the bottom of the cap) and about 200 mm above. The height of the geotextile (reference point) was marked on the tube for subsequent observations of water pressure or tension at the sand-geotextile interface. If a geotextile were to become clogged and limit flow there would be a buildup in hydraulic pressure at the interface of the geotextile and the root zone mixture as water passed through the test column. As a result, the water level in the manometer would be observed to be above the height of the surface of the geotextile. A hole was drilled through the side of the cap, into the area that contained the drainage grid, to allow for ease of drainage and to facilitate the escape of air.

A predetermined mass of each root zone mixture (based on the compaction tests) was packed into a test column, in three lifts to a total depth of 300 mm. The top of the first and second lifts were scarified to reduce layering effects. After packing, the columns were transported to the laboratory and placed on benches constructed with spaces underneath to facilitate collection of drainage water and data acquisition.

Irrigation and Data Collection

Synthetic rainwater was manufactured according to the composition reported by (Laegdsmand et al., 1999) and used throughout the duration of the experiment for all regular irrigation and data collection. At the beginning of the experiment, the columns were irrigated with 76.2 mm (3 inch) depth of water to facilitate saturation and initiate drainage. Aliquots equaling a 6.4-mm depth of synthetic rainwater were applied by hand every 15-min. In the first two weeks, the columns were irrigated with 19 mm (3/4 inch) of water every other day to simulate heavy watering during the establishment of a turfgrass cover. After two weeks the amount of water applied was reduced to half this amount. This amount of water was also applied over a two week period until the amount was once again halved. This resultant amount (4.8 mm, 3/16 inch) of irrigation was maintained throughout the rest of the study. Evaporative losses were less than 2 mm of water per day.

Drainage data collection began in July, 2008 and successive measurements were taken in August, September, October and December of that same year. These were 27 days (T1), 54 days (T2), 88 days (T3), 116 days (T4) and 171 days (T5) from the initiation of the experiment, respectively. The day preceding collection of flow data, the columns were irrigated with 25 mm of water, delivered in equal aliquots at 15-min intervals. After irrigation, the columns were covered with plastic bags to prevent evaporation while they drained overnight. Immediately before data collection commenced, the tensiometer-manometers were primed with 5 mL of water delivered with a syringe. To collect drainage data from a particular column, 25 mm of synthetic rain water was added to the top of the column instantaneously. Waters draining from test columns were collected in plastic cups. Over a period of 1-h, the cumulative mass of water that drained from the column was recorded on an electronic balance (Model SP2001Ohaus Scout Pro, Ohaus, Pine Brook, NJ) connected to a computer through a USB hub. Balance readings were recorded every five seconds over the hour-long measurement period. Six columns were tested at a given time. During the tests the water levels in the manometer-tensiometers were noted. Subsequent to the 1-h measurements, the columns were allowed to drain for 24-h and the collected drainage water was weighed. Evaporative water loss during a 1-h measurement was considered negligible. The 24-h measurements were taken beginning in August and subsequently in September, October and December, 2008. All the 24-h measurements were subsequently corrected for evaporation.

Collection of Drainage Water and Analyses

As the plastic containers in which the drainage water was collected filled, the suspended particles in the drainage water were flocculated with sodium chloride, and the supernatant was siphoned off. Particles from subsequent drainage water were similarly treated and added to previously flocculated material.

At 5 months into the study, the accumulated particles were dialyzed in a membrane having a pore size range of 12 to14 kDa and a diameter of 29 mm (Spectra/Por ® 4, Spectrum labs, Rancho Dominguez, California). The dialysis tubing containing the particles was placed in a container of distilled water and the water was periodically changed until the electrical conductivity was near that of the distilled water. To prepare the samples for particle size analysis, the dialyzed particles were dispersed with 10 mL of sodium meta-phosphate (50g/L) and mixed with a magnetic stirrer. A pipette was used to place a subsample into the laser particle size analyzer. The remaining particles were dried at 70 °C to remove excess water. The particles left after this initial drying were dried at 105 °C and weighed.

Statistical Analyses

Repeated Measures Analysis of Variance was used to assess the 15-min, 1-h and 24-h drainage data obtained over the course of the study. This was done to assess what effects the factors: Geotextile (individual geotextiles), Mixture (root zone mixture), Replicate, and Time (time from initiation of study) had on drainage. The interactions: Geotextile*Mixture, Mixture*Replicate and Geotextile*Replicate were also assessed. In addition, repeated measures analysis of variance was used to assess the influence of Geotextile Type (woven, needle punched, and spunbond) on drainage. The effect of factors was considered to be significant when $P \leq 0.05$. Posthoc tests were carried out using Fisher's Protected Least Significance test ($P \leq 0.05$) to compare individual means.

Analysis of Variance was carried out on the mass of the fines and the d_{90} size of particles which drained from the columns. This was done to assess the effect that the factors: Geotextile and Mixture had on the amount and size of fines passing the geotextiles. The statistical tests were performed using SPSS version 14.0 or 15.0 (SPSS Inc, Chicago, Illinois).

CHAPTER III

RESULTS AND DISCUSSION

General Temporal Changes in Drainage

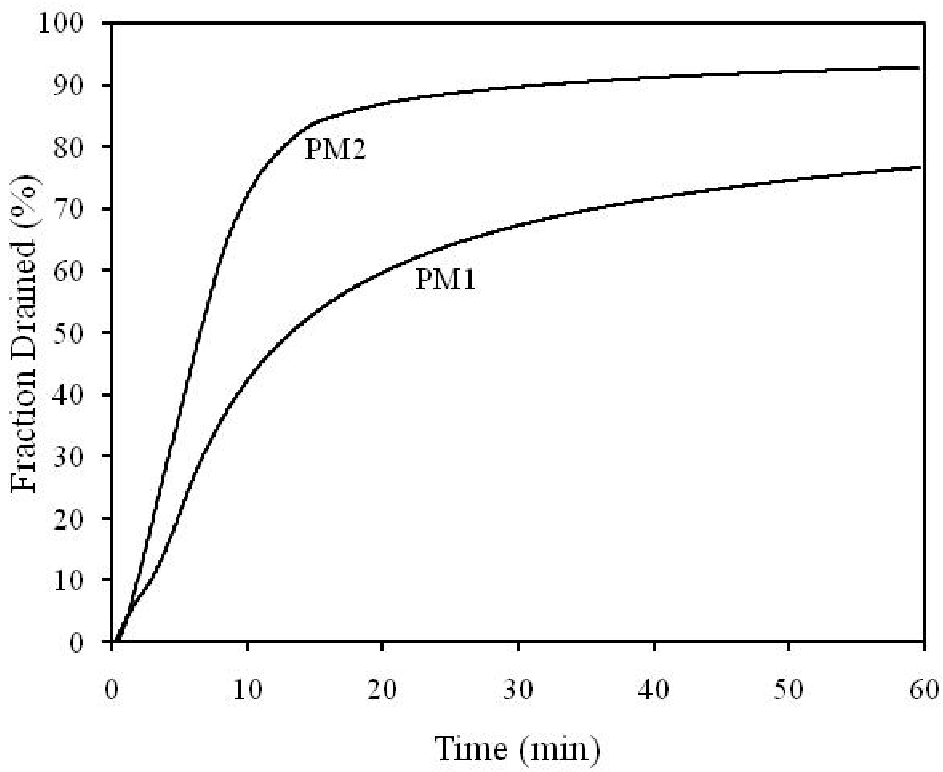

Fig.8. Typical cumulative drainage curves from the first measurement time.

The cumulative drainage from a particular treatment over the hour long measurement period produced a curve showing a decline in drainage rate with time (Figure 8). Two points were taken from each curve, the fraction of water drained after

15 and 60-min. These two points were used as a measure of the effect of a treatment and used in statistical analyses.

The shapes of the cumulative drainage curves were determined by the hydraulic and physical properties of the root zone mixtures. PM1 was the coarsest root zone mixture as indicated by its particle size distribution (Figure 6). Its relatively large pores transmitted water readily under saturated conditions (Table 3). However, this mixture

Table 3. Saturated hydraulic conductivity and coefficient of particle size uniformity of root zones mixtures.

Root zone mixture	Saturated Hydraulic Conductivity µm/s (in/h)	Coefficient of Uniformity†
PM1	330 (47)	2.55
PM2	38 (5.4)	3.17
M1	53 (7.5)	3.48
M2	58 (8.3)	4.35
M3	28 (4.0)	3.87
M4	10 (1.42)	5.96

† C_U is a descriptor of the shape of a particle size distribution curve, calculated as d_{60}/d_{10}, where d_{60} is the diameter where 60% of particles are smaller and d_{10} is the size where 10 % of particles are smaller.

desaturated more quickly than the finer textured mixtures when subjected to increasing water tension (Figure 9). It took over 30 mm water to saturate the drained PM1 profile shown in Fig. 9 so the 25 mm of water applied to test this treatment never fully saturated the profile and the drainage rate was always less than the saturated conductivity of 1.2 m/h. In comparison, PM2 was a finer textured root zone mixture. It took only a mm or two of water to saturate the PM2 profile so the 25 mm of water produced an extended drainage rate near its saturated conductivity, as indicated by the straight portion of the PM2 curve between 2 and 8 minutes (Fig 8.). The constant slope of this portion of the PM2 curve was equivalent to a drainage rate of 37μm/s. This agreed with the saturated conductivity value in Table 3.

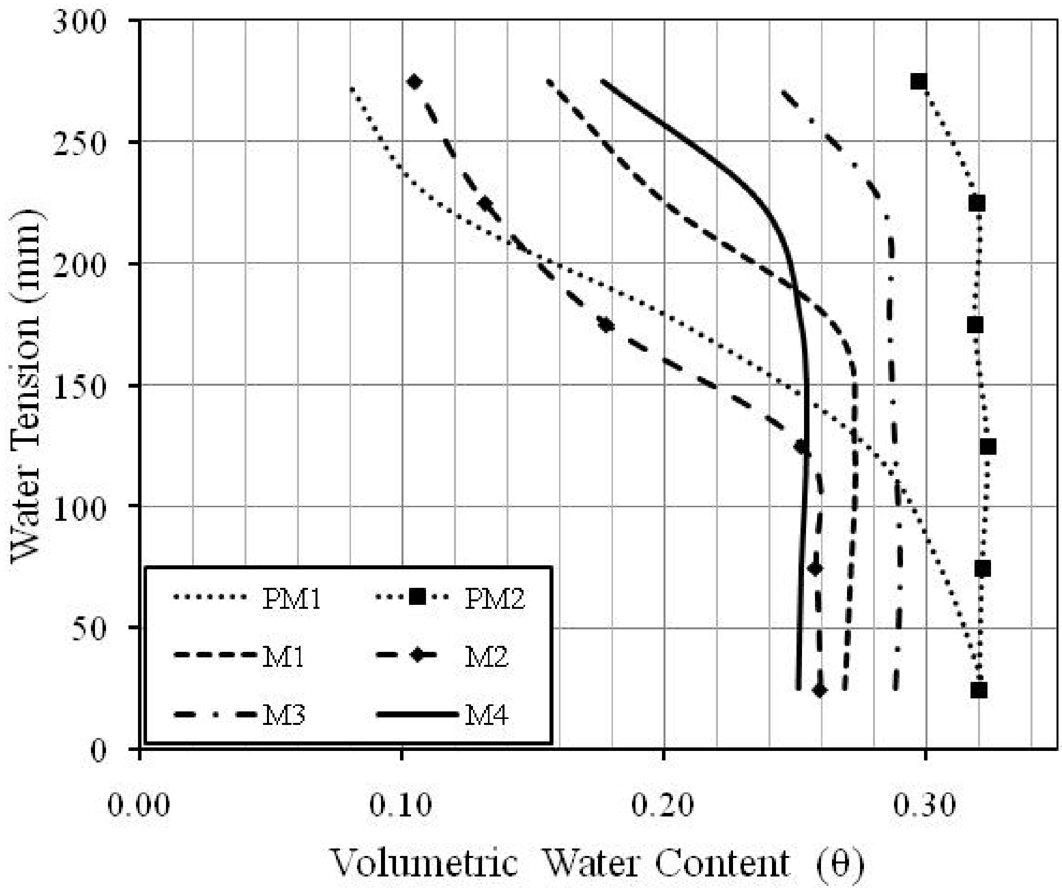

Fig.9. Water retention curves for root zones used in the study.

When drainage curves from a given data collection time were averaged across all treatments which contained the same geotextile, the effect of geotextile on drainage appeared minimal (Figure 10). On the contrary, the effect of root zone was considerable as evidenced when the drainage curves were averaged across all treatments that contained the same root zone mixture.

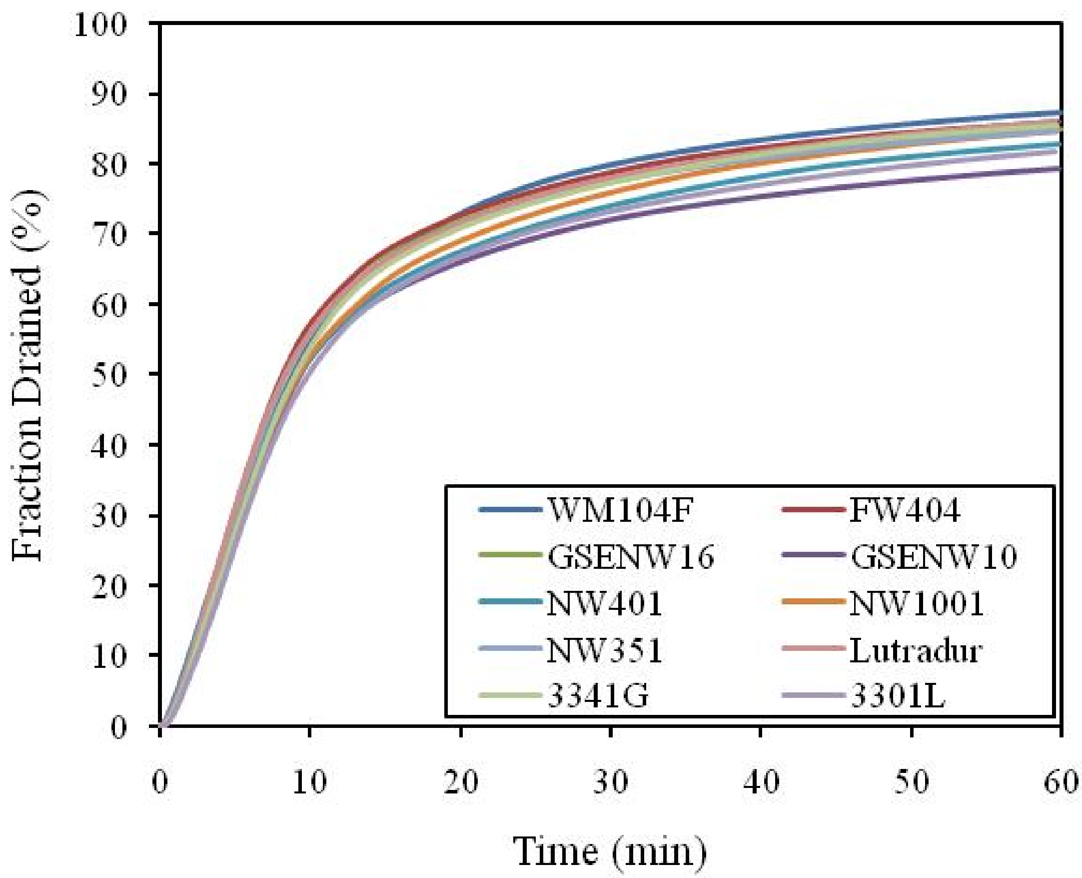

Fig.10. Average fraction drained over an hour for each geotextile in data collection time T1.

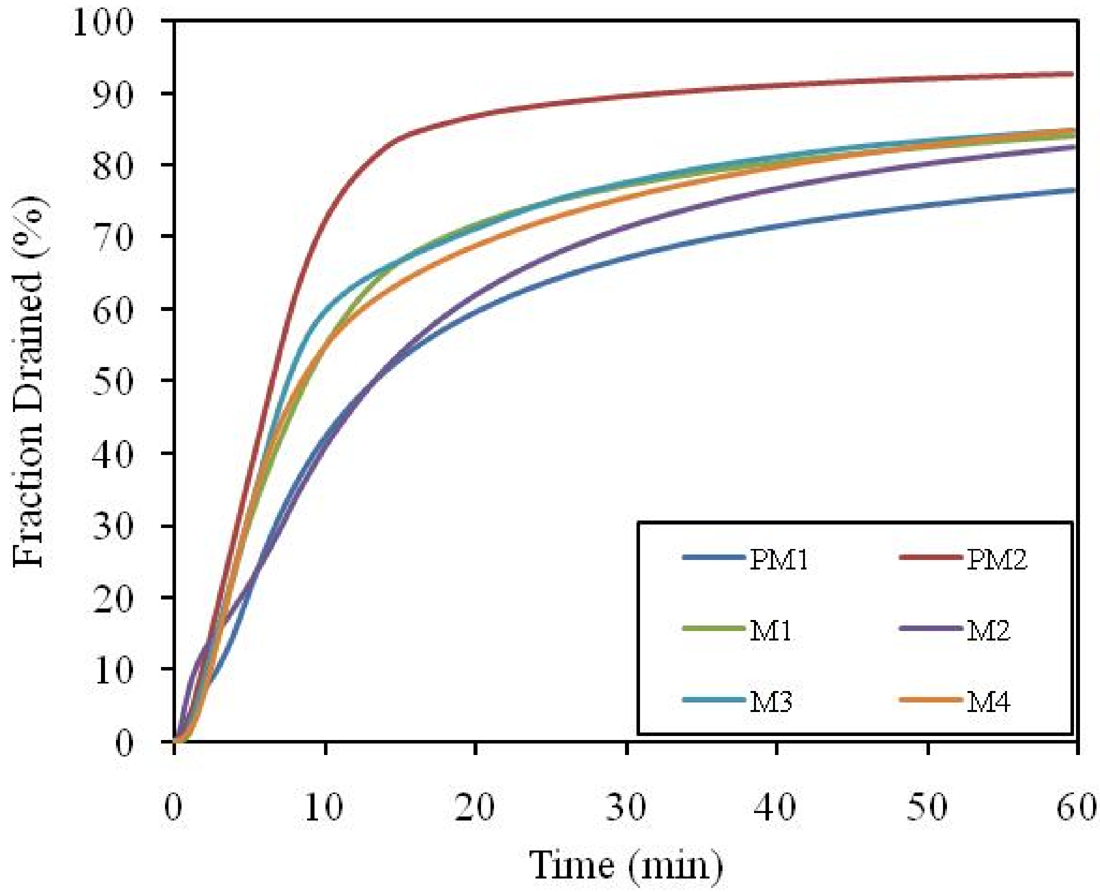

Fig.11. Average fraction drained over an hour for each root zone mixture in data collection time T1.

Statistical Analyses of Drainage

Repeated Measures Analysis of Variance was carried out on the fraction of the 25 mm of water drained in 15-min, 60-min and 24-h after application. Values were analyzed for the effect of Mixture, Geotextile, Replicate and their respective two-way interaction terms. Root zone mixture was the main influence on drainage regardless of the time that had passed since the application of water, as indicated by the partial eta squared values (Tables 4-6). Geotextile influence was not significant at 15-min (Table 4) or at 24-h (Table 6). However, geotextile influence was significant at 1-h after water application (Table 5).

Table 4. Repeated measures analysis of variance on water drained from test columns from T1 to T5 for the first 15-min after 25 mm water application.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance †	Partial Eta Squared
Intercept	3251000	1	3251000	24570	.000	.996
Mixture	106000	5	21200	160.2	.000	.899
Geotextile	2120	9	253.5	1.780	.083	.151
Replicate	2733	2	1367	10.33	.000	.187
Mixture X Geotextile	8902	45	197.8	1.495	.054	.428
Mixture X Replicate	299900	10	299900	226.6	.000	.962
Geotextile X Replicate	2202	18	122.3	.925	.552	.156
Error	11910	90	132.3			

†Values < 0.05 are significant at P=0.05.

Table 5. Repeated measures analysis of variance on water drained from test columns from T1 to T5 for the first 1-h after 25 mm water application.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance †	Partial Eta Squared
Intercept	5950000	1	5949000	51360	.000	.998
Mixture	37570	5	7514	64.88	.000	.783
Geotextile	2942	9	326.9	2.822	.006	.220
Replicate	4810	2	2405	20.76	.000	.316
Mixture X Geotextile	6693	45	148.7	1.284	.157	.391
Mixture X Replicate	149500	10	14950	129.1	.000	.935
Geotextile X Replicate	2587	18	143.7	1.241	.247	.199
Error	10420	90	115.8			

†Values < 0.05 are significant at P=0.05.

Table 6. Repeated measures analysis of variance on water drained from test columns from T2 to T5 for the first 24-h after 25 mm water application.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance †	Partial Eta Squared
Intercept	6036000	1	6036000	393400	.000	1.000
Mixture	978.9	5	195.8	12.76	.000	.441
Geotextile	166.2	9	18.46	1.203	.305	.118
Replicate	224.8	2	112.4	7.325	.001	.153
Mixture X Geotextile	576.4	45	12.81	.835	.743	.317
Mixture X Replicate	589.2	10	58.92	3.840	.000	.322
Geotextile X Replicate	540.3	18	30.02	1.956	.022	.303
Error	1243	81	15.35			

†Values < 0.05 are significant at P=0.05.

When individual geotextile names were replaced by their Type (i.e. woven, needle punched, and spunbond) and Repeated Measures Analysis of Variance carried out on the drainage data, the analysis revealed that Geotextile Type was not a significant influence on drainage at 15-min (Table 7) and 24-h (Table 8) after water application. However, Geotextile Type did significantly influence drainage at 1-h (Table 9).

Table 7. Repeated measures analysis of variance on water drained from test columns from T1 to T5 for the first 15-min after 25 mm water application, replacing Geotextile with Geotextile Type.

Source	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F**	**Significance †**	**Partial Eta Squared**
Intercept	2856000	1	2856000	18830	.000	.992
Mixture	88500	5	17690	116.7	.000	.800
Replicate	2679	9	1339	8.831	.000	.108
Geotextile Type	414.5	2	207.2	1.366	.258	.018
Mixture X Geotextile Type	1632	10	163.2	1.076	.384	.069
Mixture X Replicate	299900	10	29990	197.7	.000	.931
Geotextile Type X Replicate	944.9	4	236.2	1.558	.189	.041
Error	22140	146	151.7			

†Values < 0.05 are significant at P=0.05.

Table 8. Repeated measures analysis of variance on water drained from test columns from T2 to T5 for the first 24-h after 25 mm water application, replacing Geotextile with Geotextile Type.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance †	Partial Eta Squared
Intercept	5385000	1	5385000	324000	.000	1.000
Mixture	900.9	5	180.2	10.84	.000	.283
Replicate	105.8	2	52.89	3.180	.045	.044
Geotextile Type	32.96	2	16.48	.991	.374	.014
Mixture X Geotextile Type	131.2	10	13.12	.789	.639	.054
Mixture X Replicate	630.3	10	63.03	3.791	.000	.217
Geotextile Type X Replicate	169.7	4	42.42	2.551	.042	.069
Error	2278	137	16.63			

†Values < 0.05 are significant at P=0.05.

Table 9. Repeated measures analysis of variance on water drained from test columns from T1 to T5 for the first 1-h after 25 mm water application, replacing Geotextile with Geotextile Type.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance †	Partial Eta Squared
Intercept	5253000	1	5253000	39760	.000	.996
Mixture	30700	5	6147	46.53	.000	.614
Replicate	4181	2	2090	15.83	.000	.178
Geotextile Type	1849	2	924.2	6.997	.001	.087
Mixture X Geotextile Type	1274	10	127.4	.965	.477	.062
Mixture X Replicate	149500	10	14950	113.2	.000	.886
Geotextile Type X Replicate	236.5	4	59.12	.448	.774	.012
Error	19300	146	132.1			

†Values < 0.05 are significant at P=0.05.

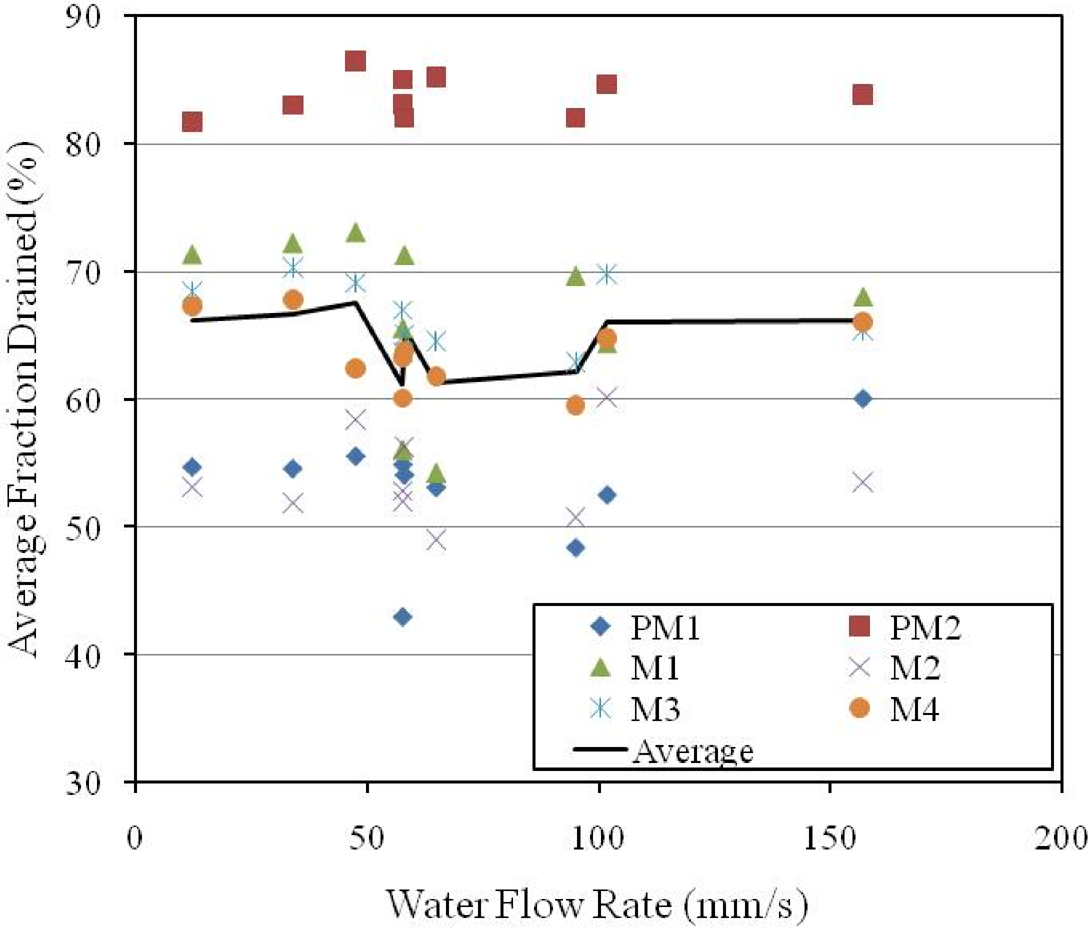

Figure 12: Relationship at T1 between fraction of water drained after 15-min and the manufacturers reported water flow rate of geotextiles. Each point represents the fraction drained for one of the ten geotextiles averaged over a given root zone mixture.

The manufacturers' reported flow rate for a geotextile had little influence on drainage from the test columns. At T1, there was no significant correlation (P=0.05 or P=0.1) between the amount of water that drained through a geotextile after 15-min and the reported water flow rate of that geotextile (Figure 12 and Table 10). By the end of the study, there was significant correlation (P=0.1) for PM1 and PM2 (Figure 13 and Table 10).

Table 10. Pearson's correlation coefficients between the fractions of water drained after 15-min and the manufacturers reported water flow rates for the geotextiles.

Rootzone Mixture	Pearson Correlation Coefficients, r †				
	T1	**T2**	**T3**	**T4**	**T5**
PM1	0.216	0.420	0.348	0.513	0.611
PM2	0.413	-0.186	-0.226	0.043	0.625
M1	-0.141	-0.022	0.032	0.162	0.389
M2	0.106	-0.099	-0.314	-0.345	-0.260
M3	-0.339	-0.136	-0.009	0.129	0.445
M4	-0.131	-0.260	-0.283	-0.346	-0.349

† For $r \geq 0.549$ and $r \geq 0.632$, the probability is .10 and .05 respectively for ten pairs of unrelated observations.

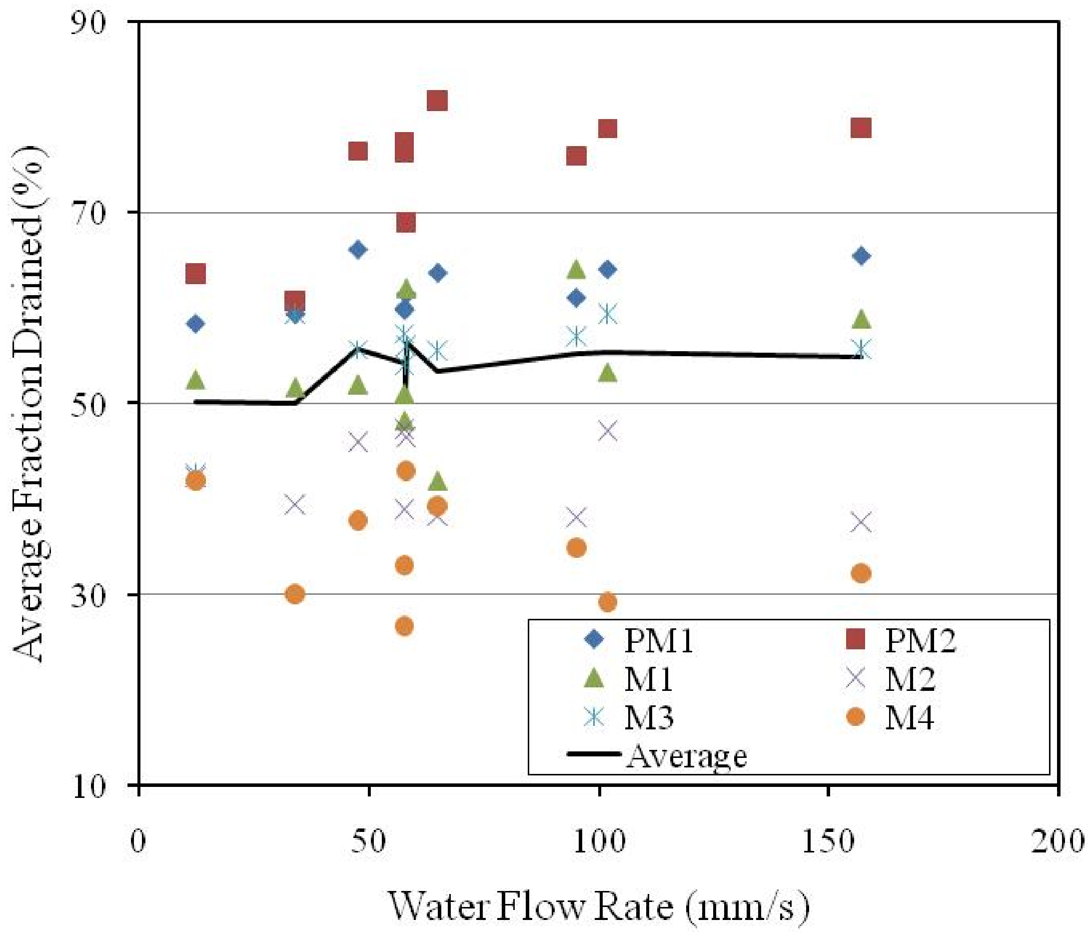

Fig.13. Relationship at T5 between fraction of water drained after 15-min and the manufacturers reported water flow rate of geotextiles. Each point represents the fraction drained for one of the ten geotextiles averaged over a given root zone mixture.

There was a significant decline in average drainage observed over the course of the study. This was particularly apparent in 15-min and 1-h drainage fractions, as revealed by repeated measures analysis of variance which was undertaken to assess if these drainage fractions at T1, T2, T3, T4 and T5 were significantly different. Fisher's Least Significant Difference comparisons revealed that 15-min and 1-h drainage fractions at T3, T4 and T5 were all significantly lower than at T1 and T2.

There were several columns that showed more appreciable decreases in the fraction of water drained than others. This was observed for root zone mixtures in particular replicates. All Replicate 1 columns that contained root zone M4 and all Replicate 2 columns that contained root zone M3 showed a reduction in drainage that was appreciably more than their counterpart replicates. With root zone mixture M4, the drainage fraction from Replicate 1 after an hour was less than 1/3rd of Replicates 2 and 3 (Figure 14). Standing water was observed on the surface of several of these columns 1 hour after water application. Observations of the manometer-tensiometers with their sensors placed between the root zone mixture and the geotextile showed that there were no appreciable or sustained positive pressures during drainage of these underperforming columns. Although geotextile somewhat influenced drainage (Table 5 and Table 8), the tensiometer- manometer observations suggest that the geotextiles were not the main factor limiting drainage, but that deterioration in the permeability of the root zone mixture was the cause. Further study is warranted to determine what led to the observed

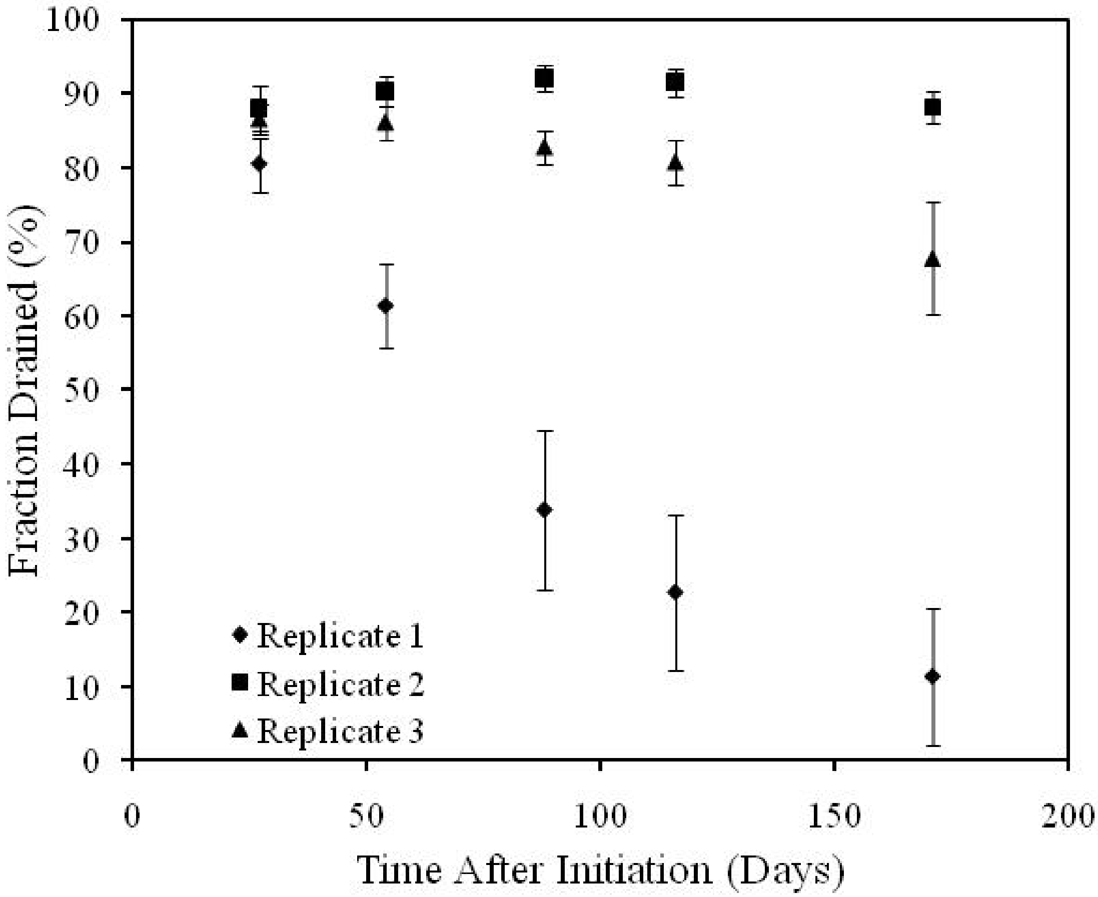

Fig.14. Fraction of water drained (%), over 1-h, from test columns containing root zone mixture M4 for all data collection periods and replicates. The error bars represent the 95% confidence interval. N=10.

decreases in drainage. This could be done by measuring the whole system saturated hydraulic conductivities, removing given increments of root zone mixture and repeating the saturated hydraulic conductivity measurements on the remaining root zone. The root zone mixture that would be removed from each layer could be assessed for fines. At the completion of this thesis research, no conclusions could be drawn because it would have required data obtained through premature destructive sampling of the columns.

Soil Particles in Drainage Water

Most of the particulate matter lost from the columns in the drainage water were within the silt to clay range (50 µm <d < 2 µm). On average, 50 % of the particles were less than 11 µm diameter. Most columns lost less than 2% of their fines (particles with d < 150 µm) through 5 months, after which most drainage water was relatively free of particles. The test columns that contained M2 lost 4-6 % of their fines. It was observed that the amount of particulate material lost from a particular root zone was similar regardless of the geotextile. This suggests that the root zone mixture, not geotextile, had the main influence on the amount and size of fines lost. The statistical analysis carried out on the mass of particles in the drainage water further supported this finding (Table 11).

Table 11. Analysis of variance on the mass of particles in drainage water.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance†
Model	58220	60	970.3	7.490	.000
Mixture	45570	5	9114	70.35	.000
Geotextile	42.77	9	4.752	0.037	1.000
Mixture x Geotextile	230.7	45	5.127	0.40	1.000
Error	15550	120	129.6		
Total	73760	180			

† Values < 0.05 are significant at P=0.05.

The data obtained from the analysis showed that each root zone mixture was releasing distinctly different size ranges of particles (Figure 15). However, there was no evidence that the geotextiles were acting as sieves. If this were the case, it would be

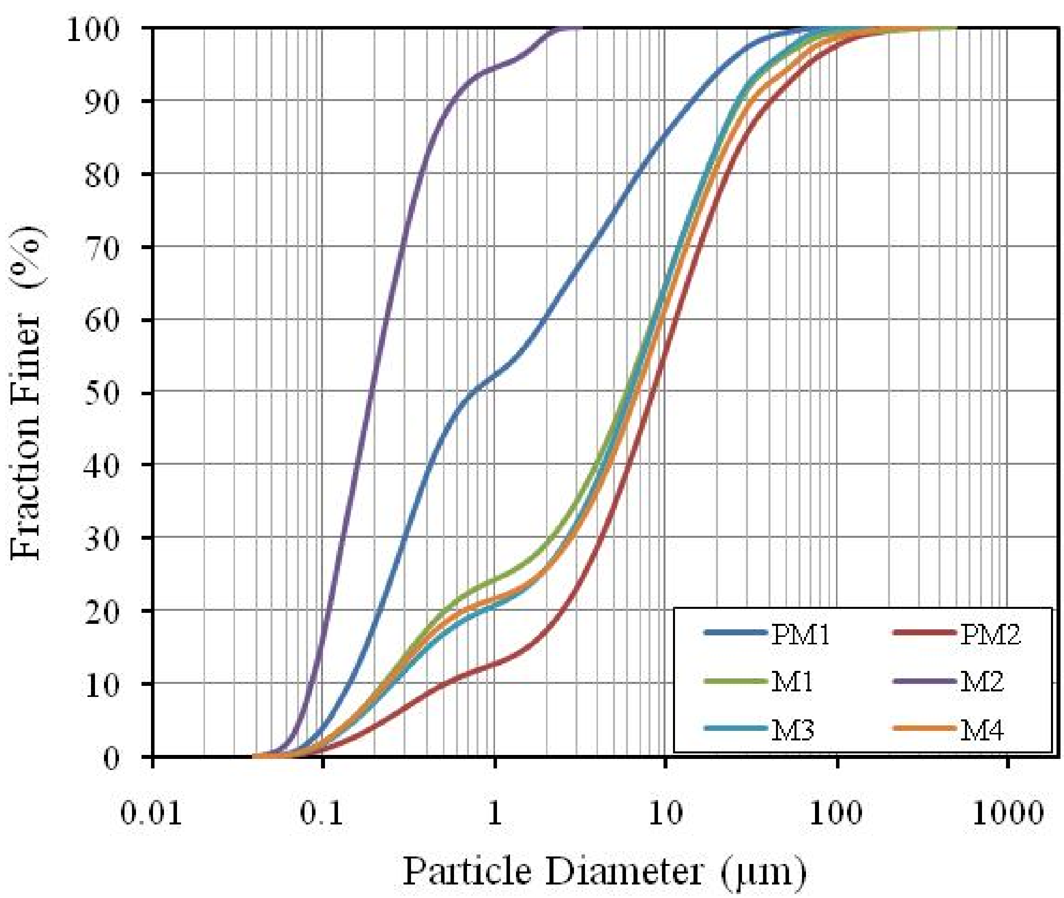

Fig.15. Size distributions of particles in the drainage waters averaged across all geotextiles. N=10.

expected that the maximum size of particles that passed through a given geotextile would be close to its AOS. This was not the case. For example, the geotextile FW404 has the greatest AOS (0.425 mm), but the distribution and maximum size of particles that passed through this geotextile from root zone mixture M2 was similar to that from all other geotextiles, and almost all particles were less than 3 µm diameter (Figure 16). These data suggested that the range and maximum size of particles passing though the geotextiles from the columns were being more greatly influenced by the root zone

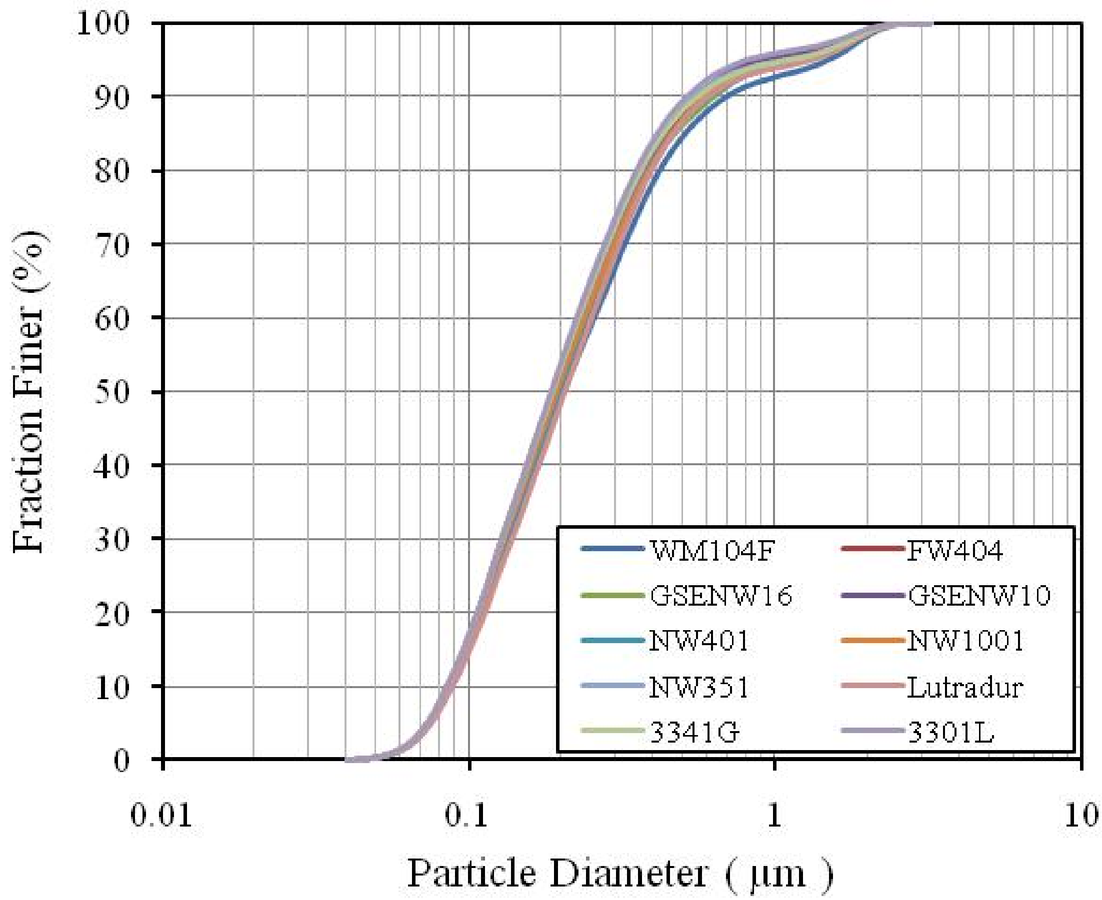

Fig.16. Size distributions of particles in drainage waters of root zone mixture M2 for each geotextile.

mixture, than the geotextile. The statistical analysis on the carried out the d_{90} sizes of the particles in the drainage water provides further proof of this (Table 12). When the

Table 12. Analysis of variance on the d_{90} size of particles in drainage water.

Source	**Sum of Squares**	**df**	**Mean Square**	**F**	**Significance†**
Model	177800	15	11850	20.66	.000
Mixture	42850	5	8569	14.93	.000
Geotextile	4085	9	453.9	0.791	.625
Error	94680	165	573.8		
Total	272500	180			

† Values < 0.05 are significant at P=0.05.

size distribution of particles that were lost from the columns was averaged across all root zone mixtures for a given geotextile, similar curves were produced (Figure 17). If geotextile were the main factor influencing the size of particles passing out of the root zone mixtures with the drainage water it would have been expected that the curves produced would show greater difference and that the maximum size of particles passing through a geotextile would have been more in line with its AOS.

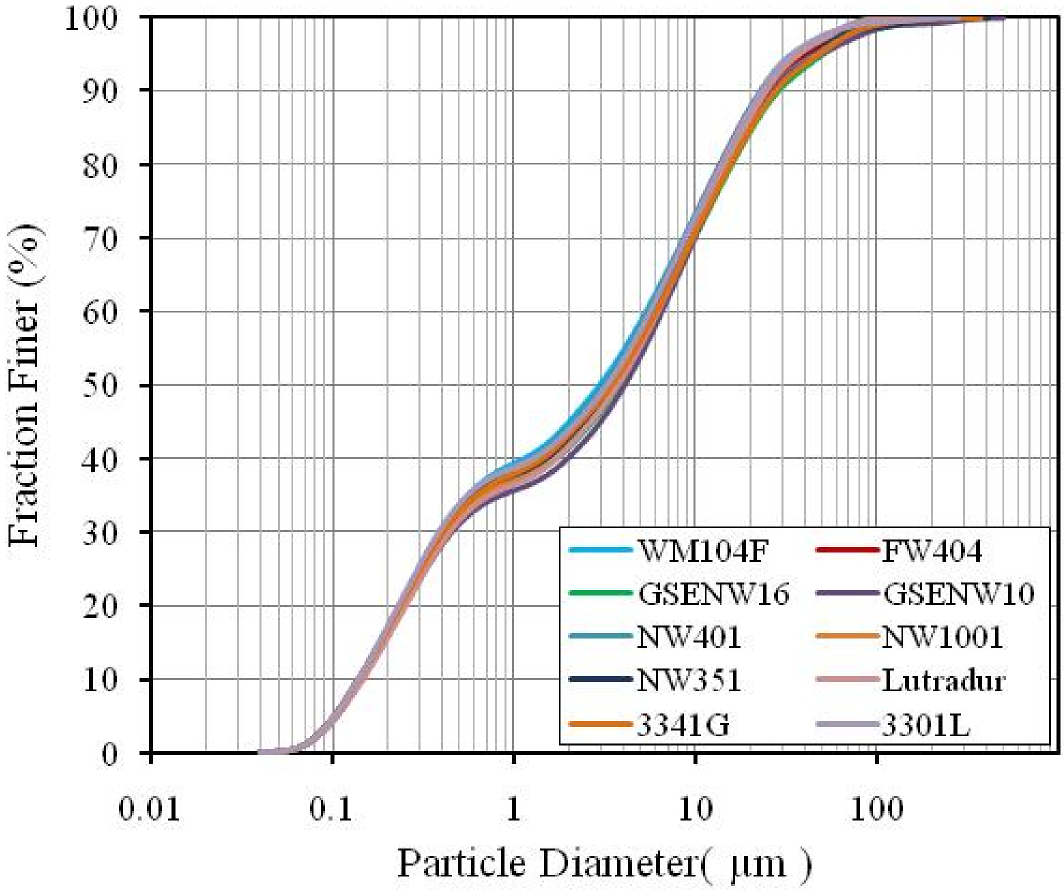

Fig.17. Size distributions of particles in drainage waters averaged across all root zone mixtures. N=6.

CHAPTER IV

CONCLUSIONS

The physical properties of the root zone mixture had a more significant influence on drainage rates than the physical properties of the geotextiles. The amount and size distribution of particles lost from the test columns were influenced by the properties of the root zone mixtures, but not by the properties of the geotextiles. Some declines in the drainage fraction were observed with time, but it appeared that these were mostly a result of reduction in permeability of the root zone mixtures.

In conclusion, when establishing a sports field constructed using root zone mixtures meeting USGA recommendations over geotextiles with AOS between 0.150 and 0.425 mm, minimal reduction in the drainage fraction due to clogging of the geotextile would be expected.

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APPENDIX A

TWENTY FOUR HOUR DRAINAGE DATA

Table A-1. Average fraction (%) of drainage from test columns 24-h after application of 25 mm water 54 days after initiation.

Geotextile	Root Zone					
	PM1	PM2	M1	M2	M3	M4
WM104F	97.73	98.27	97.99	100.70	97.82	98.49
FW404	94.56	98.62	96.61	100.46	98.98	97.13
GSENW16	94.10	98.57	99.05	99.70	98.76	98.33
GSENW10	97.20	97.25	96.83	97.84	98.16	97.41
NW401	96.93	98.27	97.69	99.16	98.10	98.03
NW1001	96.82	97.32	97.20	99.10	97.51	97.14
NW351	96.52	96.94	96.87	98.54	98.11	97.41
Lutradur	97.32	98.96	96.58	99.42	98.45	97.60
3341G	95.42	97.70	97.05	98.98	97.72	96.35
3301L	96.11	97.55	96.68	99.24	96.97	97.74

Table A-2. Average fraction (%) of drainage from test columns 24-h after application of 25 mm water 88 days after study initiation.

Geotextile	Root Zone					
	PM1	PM2	M1	M2	M3	M4
WM104F	94.94	97.98	97.53	98.63	97.20	98.97
FW404	93.17	97.30	97.07	100.65	97.12	97.22
GSENW16	92.00	97.19	98.30	98.19	98.08	97.80
GSENW10	94.36	96.99	96.96	96.67	96.98	97.42
NW401	94.47	96.31	96.13	97.86	96.04	96.23
NW1001	95.83	96.93	96.78	97.94	96.69	95.10
NW351	93.08	97.21	96.57	98.58	96.12	96.37
Lutradur	96.18	96.91	95.74	96.84	96.82	96.29
3341G	94.44	96.50	96.36	98.75	95.89	96.08
3301L	95.88	96.99	94.92	98.35	96.39	96.97

Table A-3. Average fraction (%) of drainage from test columns 24-h after application of 25 mm water 116 days after study initiation.

Geotextile	Root Zone					
	PM1	PM2	M1	M2	M3	M4
WM104F	94.18	97.78	98.05	98.57	97.00	98.25
FW404	94.37	97.38	93.18	98.91	98.86	97.34
GSENW16	92.74	96.76	97.76	98.48	97.40	97.91
GSENW10	95.30	97.83	97.37	97.40	97.89	98.28
NW401	95.26	97.87	97.03	98.82	97.51	97.01
NW1001	96.20	97.16	96.84	98.88	97.06	96.97
NW351	94.53	96.12	96.69	98.38	96.66	95.91
Lutradur	95.95	96.17	94.69	98.77	96.54	95.56
3341G	93.42	96.56	95.34	96.75	96.52	95.63
3301L	93.00	93.95	94.02	95.55	94.55	94.34

Table A-4. Average fraction (%) of drainage from test columns 24-h after application of 25 mm water 171 days after study initiation.

Geotextile	Root Zone					
	PM1	PM2	M1	M2	M3	M4
WM104F	92.38	86.08	94.97	98.95	97.74	96.11
FW404	94.54	97.61	90.75	100.02	93.48	97.79
GSENW16	91.80	73.80	97.52	98.33	98.54	97.16
GSENW10	93.65	92.36	97.42	98.85	98.42	95.84
NW401	95.85	98.20	98.38	99.95	98.25	97.80
NW1001	95.24	97.34	96.93	99.07	97.30	93.34
NW351	93.19	97.12	97.30	98.81	98.00	91.58
Lutradur	95.17	96.77	95.73	99.36	96.30	95.51
3341G	94.71	84.69	95.93	97.99	96.99	94.50
3301L	95.73	96.07	97.39	95.97	97.97	95.48

APPENDIX B

AVERAGE FRACTION OF WATER DRAINED AS A PERCENTAGE OF WATER APPLIED FOR ALL ROOT ZONE MIXTURES OVER EACH GEOTEXTILE

Table B-1. Average fraction (%) of drainage from test columns 1-h after application of 25 mm water.

Geotextile	Root Zone	Days from Initiation of Study				
		27	**54**	**88**	**116**	**171**
WM104F	PM1	79.76	83.69	81.43	83.86	84.46
	PM2	95.05	96.58	96.65	95.59	83.19
	M1	89.49	89.76	88.80	88.66	83.65
	M2	83.10	84.46	80.09	79.75	77.31
	M3	87.26	81.31	79.82	75.81	67.21
	M4	88.17	89.01	84.28	81.91	74.43
FW404	PM1	77.82	83.65	83.43	84.12	87.00
	PM2	93.16	95.43	94.39	93.79	92.87
	M1	88.46	91.16	91.36	91.00	82.93
	M2	83.27	86.77	82.83	81.29	79.77
	M3	88.33	87.26	78.67	76.95	64.26
	M4	84.96	76.42	70.47	63.69	54.62
GSENW16	PM1	77.28	79.39	79.03	79.54	79.91
	PM2	91.57	95.16	93.62	93.41	70.11
	M1	86.77	88.68	88.28	86.80	84.13
	M2	81.15	84.01	79.28	79.12	76.15
	M3	87.24	83.72	79.62	78.10	73.22
	M4	86.05	77.78	64.32	59.09	51.83
GSENW10	PM1	67.91	78.15	77.03	78.61	81.44
	PM2	92.20	93.94	93.75	93.86	86.65
	M1	73.04	77.39	79.70	78.55	76.85
	M2	79.35	82.89	78.69	79.16	79.65
	M3	83.23	82.14	74.99	73.77	69.85
	M4	80.12	75.69	65.45	62.13	52.85
NW401	PM1	72.33	82.55	80.90	83.39	86.00
	PM2	90.92	93.83	92.23	93.15	92.46
	M1	85.23	87.58	87.21	87.36	87.67
	M2	82.63	82.83	79.72	79.40	77.01
	M3	83.13	76.17	72.72	72.68	69.30
	M4	82.62	79.94	71.76	65.52	56.41

Table B-1 Continued

Geotextile	Root Zone	Days from Initiation of Study				
		27	**54**	**88**	**116**	**171**
NW1001	PM1	78.93	82.21	82.90	84.18	82.82
	PM2	93.28	93.87	93.78	94.13	93.52
	M1	86.41	86.93	86.78	86.77	84.41
	M2	81.10	83.98	79.29	78.83	76.47
	M3	83.82	75.74	69.89	67.74	65.53
	M4	84.23	77.00	64.60	59.65	44.25
NW351	PM1	73.86	82.43	79.36	85.26	85.28
	PM2	93.13	94.38	94.71	94.02	93.93
	M1	83.35	87.19	87.29	87.77	84.93
	M2	86.43	89.75	86.72	86.33	84.55
	M3	85.27	82.54	79.02	76.79	73.29
	M4	85.54	77.41	64.89	60.19	48.48
Lutradur	PM1	82.61	84.82	86.24	86.95	88.35
	PM2	93.64	95.05	93.25	92.90	93.18
	M1	83.75	87.62	87.78	87.28	86.36
	M2	83.23	83.65	78.82	78.18	75.60
	M3	85.77	86.05	80.47	78.13	73.34
	M4	86.65	78.62	67.28	61.60	53.46
3341G	PM1	78.52	82.14	83.64	82.72	83.07
	PM2	90.79	94.00	92.17	93.00	80.18
	M1	86.02	88.89	88.59	89.38	87.23
	M2	85.87	85.64	82.90	82.82	78.99
	M3	84.50	81.67	77.61	75.77	78.99
	M4	87.47	79.38	68.11	64.91	61.00
3301L	PM1	77.38	82.10	84.51	85.28	87.47
	PM2	93.12	94.38	93.80	93.31	91.84
	M1	78.33	81.97	80.49	80.44	77.77
	M2	79.22	79.41	77.29	76.79	73.46
	M3	79.23	78.82	74.56	72.70	66.31
	M4	83.72	80.77	73.85	70.58	60.02

APPENDIX C

CUMULATIVE DRAINAGE AS A PERCENTAGE OF WATER APPLIED FOR M3 AND M4 OVER ALL GEOTEXTILES

Table C-1. Fraction (%) of drainage 1-h after application of 25 mm water to test columns containing M3.

Geotextile	Replicate	Days from Initiation of Study				
		27	**54**	**88**	**116**	**171**
WM104F	1	91.39	91.74	90.98	91.28	88.95
	2	75.01	55.09	52.85	40.14	14.43
	3	95.38	97.11	95.62	96.01	98.23
FW404	1	92.60	94.74	93.79	92.47	88.20
	2	77.75	68.17	46.38	40.74	6.26
	3	94.63	98.86	95.84	97.65	98.32
GSENW16	1	95.06	96.62	95.97	96.07	94.79
	2	69.76	56.86	45.12	42.34	27.49
	3	96.90	97.67	97.78	95.88	97.37
GSENW10	1	92.60	93.14	92.88	92.54	92.19
	2	63.61	54.86	36.30	30.58	19.47
	3	93.47	98.43	95.79	98.19	97.89
NW401	1	89.41	91.48	89.41	90.05	89.73
	2	67.99	38.93	33.38	29.87	19.96
	3	92.01	98.10	95.36	98.12	98.21
NW1001	1	90.14	91.54	90.23	91.52	89.90
	2	66.76	37.10	21.88	13.29	8.33
	3	94.55	98.58	97.56	98.41	98.36
NW351	1	92.86	94.33	93.33	93.77	93.16
	2	67.78	54.71	46.42	38.63	27.45
	3	95.18	98.58	97.30	97.97	99.25
Lutradur	1	88.05	88.22	84.98	84.57	84.29
	2	75.03	71.02	59.50	51.49	37.77
	3	94.22	98.90	96.94	98.34	97.95
3341G	1	91.13	91.72	93.27	93.18	91.20
	2	71.19	55.55	43.90	36.43	31.33
	3	91.19	97.74	95.65	97.69	97.74
3301L	1	86.97	90.90	89.97	90.74	90.14
	2	57.71	48.53	38.00	29.44	10.38
	3	93.03	97.05	95.71	97.91	98.41

Table C-2. Fraction (%) of drainage 1-h after application of 25 mm water to test columns containing M4.

Geotextile	Replicate	Days from Initiation of Study				
		27	**54**	**88**	**116**	**171**
WM104F	1	84.70	83.15	71.56	63.42	50.95
	2	87.18	93.20	94.33	93.20	88.51
	3	92.63	90.68	86.95	89.10	83.84
FW404	1	75.96	61.52	42.66	23.82	7.92
	2	94.37	85.54	88.67	86.90	80.08
	3	84.55	82.20	80.08	80.34	75.85
GSENW16	1	83.06	59.99	23.48	14.48	6.45
	2	85.95	87.28	87.53	85.78	88.26
	3	89.14	86.07	81.96	77.00	60.77
GSENW10	1	68.97	52.29	23.59	12.58	5.52
	2	90.55	94.76	94.48	94.50	89.64
	3	80.83	80.02	78.27	79.31	63.38
NW401	1	83.73	68.90	45.08	29.56	13.75
	2	80.24	86.67	90.55	89.34	88.03
	3	83.89	84.25	79.65	77.65	67.46
NW1001	1	84.12	57.51	23.35	13.21	1.75
	2	81.91	87.85	89.30	90.08	84.94
	3	86.66	85.63	81.16	75.66	46.07
NW351	1	84.96	52.59	16.36	7.88	0.86
	2	84.11	91.09	92.88	93.89	88.76
	3	87.54	88.54	85.42	78.79	55.83
Lutradur	1	83.80	58.24	26.69	15.17	4.42
	2	91.05	92.49	93.18	92.47	91.00
	3	85.11	85.11	81.96	77.17	64.96
3341G	1	83.04	56.07	19.22	10.06	4.96
	2	92.58	89.88	95.77	94.22	92.73
	3	86.79	92.19	89.33	90.44	85.31
3301L	1	71.78	62.50	45.92	36.58	16.70
	2	91.82	94.07	93.38	93.81	89.21
	3	87.57	85.74	82.24	81.36	74.15

APPENDIX D

DATA FOR PARTICLE SIZES IN DRAINAGE WATERS

Table D-1. Size characteristics of particles in drainage water.

Geotextile	Root Zone	d_{15} (µm)	d_{50} (µm)	d_{90} (µm)
WM104F	PM1	0.136	0.675	12.06
	PM2	0.713	10.16	61.32
	M1	0.213	5.381	27.29
	M2	0.0856	0.203	0.692
	M3	0.222	5.165	23.67
	M4	0.199	5.537	29.11
FW404	PM1	0.149	1.41	15.39
	PM2	0.43	7.67	34.51
	M1	0.22	5.448	24.34
	M2	0.0846	0.186	0.577
	M3	0.237	5.574	26.16
	M4	0.224	7.063	48.23
GSENW16	PM1	0.149	1.274	16.13
	PM2	0.433	8.289	46.26
	M1	0.238	6.106	30.6
	M2	0.0866	0.192	0.629
	M3	0.256	6.142	25.95
	M4	0.279	8.532	59.67
GSENW10	PM1	0.152	2.164	17.73
	PM2	0.685	8.812	59.07
	M1	0.245	6.329	31.83
	M2	0.0862	0.195	0.545
	M3	0.298	7.288	34.09
	M4	0.214	6.109	25.91
NW401	PM1	0.143	0.598	15.57
	PM2	0.549	8.301	37.17
	M1	0.232	5.94	26.91
	M2	0.0867	0.199	0.606
	M3	0.244	5.911	24.51
	M4	0.213	5.832	24.35
NW1001	PM1	0.152	0.905	20.07
	PM2	0.456	7.49	31.21
	M1	0.22	5.781	25.9
	M2	0.0853	0.192	0.592
	M3	0.283	6.563	24.49
	M4	0.245	7.254	36.87
NW351	PM1	0.144	0.715	11.88
	PM2	0.527	8.002	46.37
	M1	0.182	4.946	22.67
	M2	0.0847	0.186	0.542
	M3	0.272	6.798	27.63
	M4	0.273	7.45	30.05

Table D-1 Continued

Geotextile	Root Zone	d_{15} (µm)	d_{50} (µm)	d_{90} (µm)
Lutradur	PM1	0.137	0.64	12.97
	PM2	0.877	9.3	37.67
	M1	0.273	7.236	29.63
	M2	0.088	0.205	0.601
	M3	0.25	5.909	21.96
	M4	0.258	7.456	36
3341G	PM1	0.127	0.495	9.781
	PM2	0.704	9.528	51.05
	M1	0.237	6.505	31.38
	M2	0.0848	0.187	0.556
	M3	0.281	6.655	31.71
	M4	0.263	7.4	35.85
3301L	PM1	0.142	0.584	14.27
	PM2	0.364	7.441	28.34
	M1	0.244	6.209	27.98
	M2	0.0849	0.185	0.513
	M3	0.243	6.682	30.06
	M4	0.277	6.237	25.35

APPENDIX E

FINES DATA

Table E-1. Fines (d< 150 µm) in drainage water.

Geotextile	Root zone	Average mass of fines in drainage water(g)	Average mass of fines in drainage water / Total mass of fines in column (%)
WM104F	PM1	3.90	1.29
	PM2	0.31	0.01
	M1	0.64	0.05
	M2	46.29	5.40
	M3	0.57	0.02
	M4	0.69	0.04
FW404	PM1	3.49	1.16
	PM2	0.38	0.02
	M1	0.60	0.05
	M2	45.00	5.25
	M3	0.60	0.02
	M4	0.56	0.032
GSENW16	PM1	2.90	0.96
	PM2	0.26	0.01
	M1	0.61	0.05
	M2	45.61	5.32
	M3	0.52	0.02
	M4	0.63	0.03
GSENW10	PM1	2.93	0.98
	PM2	3.57	0.17
	M1	0.69	0.06
	M2	46.97	5.48
	M3	0.50	0.02
	M4	0.60	0.03
NW401	PM1	3.85	1.28
	PM2	0.29	0.01
	M1	0.47	0.04
	M2	41.51	4.84
	M3	0.53	0.02
	M4	0.58	0.03
NW1001	PM1	3.55	1.18
	PM2	0.27	0.01
	M1	0.68	0.06
	M2	40.64	4.74
	M3	0.50	0.02
	M4	0.48	0.03

Table E-1 Continued

Geotextile	Root zone	Average mass of fines in drainage water(g)	Average mass of fines in drainage water / Total mass of fines in column (%)
NW351	PM1	4.2	1.40
	PM2	0.24	0.01
	M1	1.00	0.08
	M2	42.40	4.95
	M3	0.49	0.02
	M4	0.59	0.03
Lutradur	PM1	4.07	1.35
	PM2	0.29	0.01
	M1	0.62	0.05
	M2	47.79	5.58
	M3	0.58	0.02
	M4	0.52	0.03
3341G	PM1	4.17	1.38
	PM2	0.29	0.01
	M1	0.65	0.05
	M2	42.57	4.97
	M3	0.66	0.02
	M4	0.66	0.04
3301L	PM1	3.83	1.27
	PM2	0.31	0.01
	M1	0.79	0.06
	M2	39.13	4.57
	M3	0.64	0.02
	M4	0.60	0.03

APPENDIX F

GEOTEXTILE MARKETERS' CONTACT INFORMATION

Geotextile	Contact Information
GSENW16, GSENW10	GSE Lining Technology Inc. 19103 Gundle Road Houston, TX 77073
FW404	TenCate Nicolan 1288 Old Cleveland Road Cornelia, Georgia, 30531
WM104F, NW401, NW1001, NW351	Propex Marketing Fulfillment Center 8822 Production Lane, Suite 104, Ooltewah, Tennessee, 37663-4510
Lutradur	Freudenberg 10035 Brookriver Drive Houston, Texas 77040
3301L, 3341G	Fiberweb 840 S.E. Main Street Simpsonville SC 29681

VITA

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